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AIR FORCE HUMAN RESOURCES LABORATORY

WIDE-ANGLE, MULTIVIEWER INFINITY DISPLAY DESIGN

By

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AIR FORCE SYSTEMS COMMAND
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NOTICE

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This technical report has been reviewed and is approved for publication.

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There has long been a need in aircraft simulation for a wide angle visual display that will accommodate the entire crew of a large aircraft type such as a bomber or tanker.

This study is concerned with the approach and design of a wide angle display for multiple crew members in large aircraft simulators. The study traces the development of a concept from existing simulation methods.

Throughout its 180 deg by 60 deg field of view which accommodates pilot, copilot, and instructor pilot the final design meets most of the requirements of the original specification. Because of its relatively large optical components the fabrication of the display will be of a developmental nature itself.

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WIDE-ANGLE, MULTI-VIEWER INFINITY DISPLAY

SECTION 1

INTRODUCTION, SUMMARY, RECOMMENDATIONS

1.1 INTRODUCTION

Air Force Training requirements for cockpit crews on large bomber, cargo, and tanker aircraft dictate the need for an out-the-window visual simulation capability with large fields of view and a large viewing volume within the cockpit. Although significant technological advances have been achieved in recent years in the generation of simulated imagery to serve this requirement, the provision of a completely adequate display remains a severe technical challenge.

The Wide-Angle, Multi-Viewer, Infinity Display (WAMVID) requirement involves a combination of conflicting demands on basic optical elements that can be configured in a wide variety of candidate solutions. There exist wide-angle displays such as Advanced Simulator for Pilot Training (ASPT), Navy Flight Simulators 2F90 and 2B35, and dome displays such as Large Amplitude Multimode Aerospace Research Simulator (LAMARS). However, all are seriously deficient in some respect for WAMVID. ASPT is wide angle and collimated but is monochromatic and operates with a very limited head volume. The 2F90 and 2B35 are wide angle and accommodate a relatively large viewing volume but are not collimated. The same is true for all dome displays although the lack of collimation becomes less objectionable as the dome becomes larger. There exists a collimated color display that is visible to all crew members of a wide cockpit simulator, but it has a relatively small field of view, 50 degrees by 38 degrees. The standard CRT, mirror, beamsplitter display combination fulfills many of the WAMVID requirements admirably but does not lend itself to mosaicking into large panoramic displays.

In this study, consideration of the pros and cons of the many optical configurations that might be used as a starting point eventually led to one consisting of a concave mirror collimator and off-axis screen object surface. Figure 1, which is the proposed system of this report, illustrates the concept. This configuration has the apparent capability for complete scene continuity throughout the 180 degrees by 60 degrees field for all observation positions within the viewing volume while providing a virtual color image. It is difficult to conceive of another optical arrangement that provides the total same initial capability.

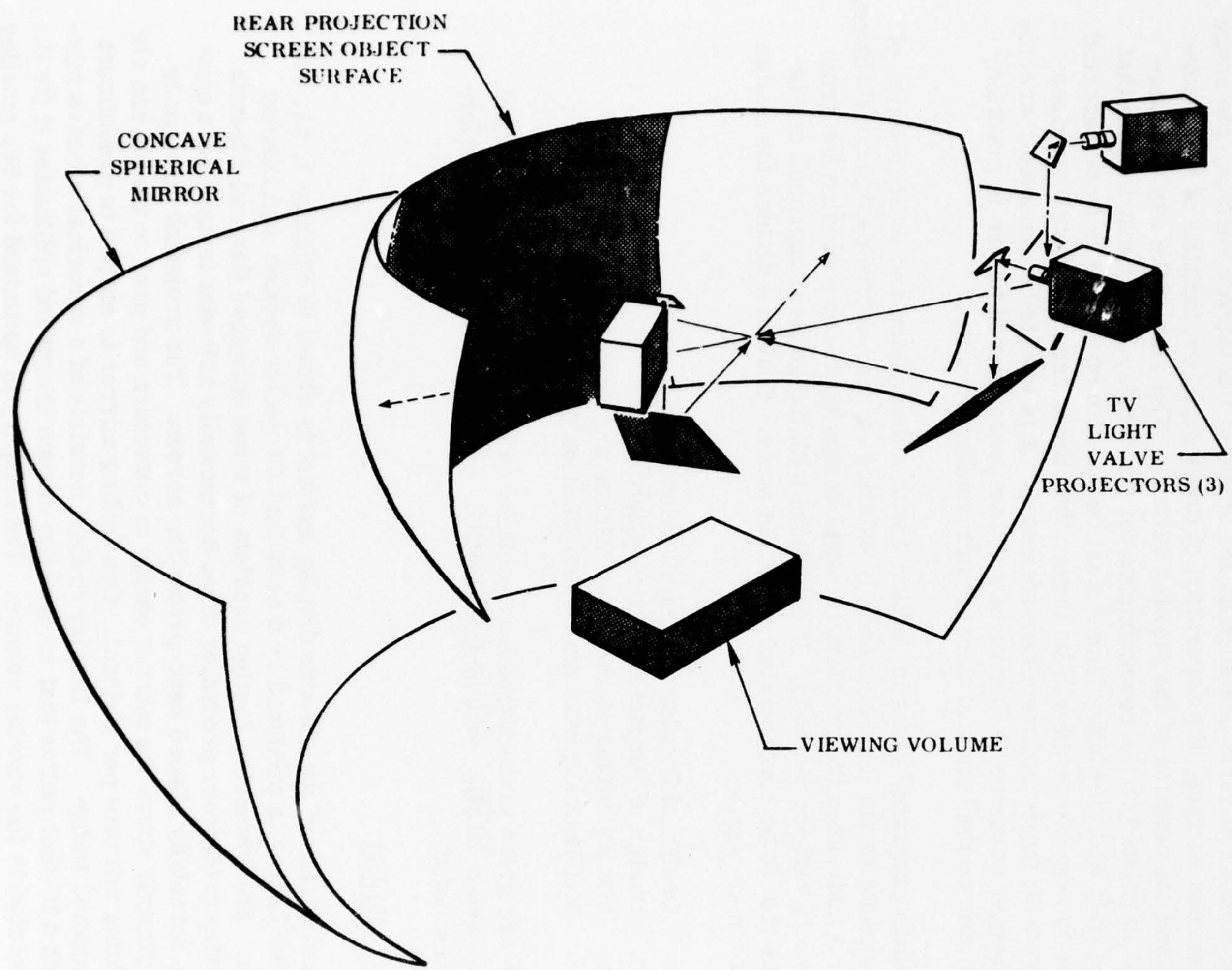

Figure 1. Proposed Wide-Angle, Multi-Viewer, Infinity Display

Because of its large angular coverage, its degree of off-axis operation, and the unusual size of its components, there are, in addition to the favorable aspects, initial questions about its image quality, distortion, size and weight, and manufacturability. The system has at its disposal for image correction a limited number of variables such as the shape of the mirror surface, the shape of the screen surface, the separation of these surfaces, the tilts of these surfaces, and the position of the viewing volume. The size of the system components is related to the requirements for the display. It almost follows that if large field and viewing volumes must be accommodated, it is to be expected that the system elements will be larger than those associated with previous displays with more moderate requirements. It is also to be expected that some of the larger components, never having been encountered before in practice, may border on the "state of the art" in manufacturability.

The design program begins in Section 2 with a discussion and interpretation of requirements in the light of presently existing or near-future design capabilities. Section 3 addresses the problem of initial design approach including the pros and cons of various methods. It concludes with the general approach of Figure 1 as that to be concentrated on in this study. Section 4 divides the design into four main areas:

a. Design of Display Section (Section 5).
b. Design of Projector Section (Section 6).
c. Manufacturing Methods for Mirror and Screen (Section 7).
d. Mechanical Structure Design (Section 8).

Details are given in the above four sections on the design approaches used, data on design details, vendor information, computer results, and performance expected.

1.2 SUMMARY

The final design of the off-axis display system is shown in Figures 1, 22, and 37. The display is produced by a combined Projector Section and Display Section. The Projector Section consists of three enhanced General Electric light valve projectors producing three horizontally adjacent images on a panoramic toroidally shaped rear-projection screen. The projector light paths cross directly above the mirror center of curvature and pass to the screen via two folding mirrors per channel. One folding mirror is shaped to pre-distort the projected image. The Display System consists of a spherical concave mirror with a 16-foot radius that accepts the screen image and collimates it for the crew located in the viewing volume. The imagery is optimized for two smaller cubical volumes 8 inches on a side whose centers are located 6 by 6 by 6 inches from the lower front left and right corners respectively, of the main viewing volume.

The system deviates from the desired results in certain areas. Because of the very large field coverage and viewing volumes, completely acceptable optical performance cannot be obtained throughout the viewing volume for the whole field of view. By accepting a graded field of view concept, which is derived from actual aircraft cockpit characteristics, relief is obtained and acceptable performance can be obtained. In this concept the front face and left and right faces of the viewing volume, when looking outward, are expected to cover the full 180-degree by 60-degree field. At the rear face of the viewing volume, as in real aircraft cockpits, the requirement on vertical field of view is reduced to 40 degrees. For the cross-cockpit view the field requirement is further reduced to 30-degree vertical. The latter is typical of the pilot looking through the copilot's window. Corresponding to the variation of optical performance throughout the viewing volume, the system was optimized for two 8-inches-on-a-side cubical volumes whose centers are located at 6 inches by 6 inches by 6 inches from the lower front left and right corners. These volumes represent nominal head positions for pilot and copilot.

It was not possible to obtain the desired collimation of 0-convergence to 4-milliradians divergency. Most of the analyzed values did comply with the MIL-HDBK-141 standard of 17-arc minutes for divergence, convergence, or dipvergence.

Preliminary structural design has shown that the display system moments of inertia and weights exceed the capacity of existing motion systems. It is concluded that the system recommended in this report cannot be used on those existing platforms. The size and weight of the components of a system that has 180-degree by 60-degree field coverage, while accommodating a viewing volume of 5 feet by 3 feet by 1-1/2 feet, simply does not lend itself to state-of-the-art cockpit motion devices.

Table 1 summarizes the characteristics and expected performance of the system described above.

1.3 RECOMMENDATIONS

The recommendations for further work are concerned with improvements to the described system. A reduction in size might be obtained when designing for specific applications. A particular aircraft might not require the full viewing volume as described in this general study. Another aircraft might employ a crew arrangement or have a window configuration that might lead to reduction in size or change in position or shape of the viewing volume or field of view.

Further research on lightweight large mirror production would not only be rewarding in this application but to many other fields. These include the entire simulation field, astronomy, aerial survey, and solar energy collection.

Table 1. Display Characteristics

1. Mechanical		
	Min	Max
Weight	6160 lbs.	14600 lbs.
Moment of Inertia		
1. About Display C G		
Roll	21800 lb-ft-sec^2	54400 lb-ft-sec^2
Pitch	14600 lb-ft-sec^2	27500 lb-ft-sec^2
2. About Motion Base		
Roll	42000 lb-ft-sec^2	89000 lb-ft-sec^2
Pitch	35000 lb-ft-sec^2	62000 lb-ft-sec^2
Overall Size Dimensions:	22 ft. high × 29 ft. front to back × 34 feet wide	
2. Optical		
	Desired	Design
Field of View	180° × 60°	(Graded field concept) 180° × 60° in optimized viewing volumes and front face of viewing volume, 180° × 40° at rear face of viewing volume, 30° vertical cross-cockpit
Viewing Volume	5 ft. wide × 3 ft. fore and aft × 1 1/2 ft. depth	Same with optimized smaller volumes of 8" × 8" × 8" at 6" × 6" × 6" from lower front left and right corners
Distortion	< 5% of vertical field of 60° or < 3°	< 5% from either 8" × 8" × 8" volume going from pilot left or copilot right to 30° azimuth to pilot's right or copilot's left of forward < 5% in graded field

Table 1. Display Characteristics (Continued)

	Desired	Design
Collimation Error	0 convergence to 4 milliradians divergency	Less than 5% of values outside of ±17 arc minutes divergence or dipvergence as specified in MIL-HDBK-141 Slightly more than 50% exceed desired collimation error
Resolution	6 arc-minutes center; 8 arc minutes corner (per line pair)	0.36 MTF at 4.5 arc minutes at the center of each of the 3 channels fall off to 6 arc-minutes in the corners of each channel
Highlight Brightness	6 footlamberts	2.3 footlamberts with plain diffuse rear projection screen Up to 11.9 footlamberts with "Fresnel prism" screen
Brightness Variation	< 25% over entire field	< 75% over entire field
Contrast Ratio	20:1	Worst condition 12:1 with "Fresnel prism" screen Worst condition 5.5:1 with plain diffuse screen
Joints	Less than 30 arc minutes gap in imagery	No gap in imagery
Image Registration	Image discontinuity less than one degree	No discontinuity
Color	Minimal color shift—minimal color variation	Complies

Table 1. Display Characteristics (Continued)

	Desired	Design
Mapping	Linear image to pilot using linearly scanned television input device	Linear discounting distortion errors—television input linear

The search for a very high brightness, high resolution relatively lightweight television projection means would also be of great value in simulation applications. One such approach is now being pursued in a study awarded by the Air Force Human Resources Laboratory (AFHRL). There are numerous other methods mentioned in this report, that also appear promising. Some of these[1] are fluid deformation and Schlieren optics, membrane deformations and Schlieren optics, photochromic effects, and laser scanners. General Electric, in addition to increasing their light valve projector resolution to 800 lines, is close to attaining 1000 lumens output.

A recommended area for further work is the design and fabrication of the rear-projection screen. The report mentions the use of proper diffusive coating materials and a fresnel prism surfacing for obtaining the unique light distribution that is needed. A lenticular construction might also be considered. The variety of solutions that might be obtained would be a good subject for further study.

[1] Good, W.E., "Projection Color Television Display Systems," MIT/SID Seminar, Session 5-6, April 18 and 22, 1977

SECTION 2

TECHNICAL REQUIREMENTS

2.1 GENERAL

The product of this study effort is to comply as closely as possible with the technical requirements in the original Statement of Work considering these requirements as guides rather than technical limits. These technical requirements are restated exactly in Figure 2.

2.2 DISCUSSION OF REQUIREMENTS

2.2.1 DISPLAY CONFIGURATION

This requirement states that the display is to be designed for mounting on a moving platform and that the display elements shall not violate any existing cockpit features but shall be mounted to surround that cockpit and be located more or less forward and above it.

There are two considerations that should be brought to attention at this point. One is that in a display of this type, size extension beyond that of present simulator configurations is to be expected because of the large field and viewing volume requirements. The increased size and bulkiness are at variance with the need for moving platform compatibility, and although it is not impossible to comply with this requirement, it represents a difficult area.

2.2.2 FIELD OF VIEW

The 180-degree by 60-degree field of view is certainly of a size warranted by present needs for simulation effectiveness.

2.2.3 VIEWING VOLUME

It is desirable to supply a unit display that provides for simultaneous unimpeded observation by all members of a large aircraft crew. This includes aircraft commander, copilot, and instructor pilot (IP). However, examination of the positions of the members of the crew on typical aircraft flight decks and the real fields of view available from those positions reveals considerably less than the 180-degree by 60-degree field available at many of them.

4.1 Display Configuration. The display system shall be designed to be mounted on a simulator motion platform. The display may surround the simulator cockpit but shall not extend into the cockpit. The display system shall not extend into the cockpit. The display system shall not extend below the cockpit floor but may extend above and away from the cockpit. The display system design shall minimize the weight which the motion platform shall carry. The design shall also consider maintenance and optics cleaning requirements.

4.2 Image Requirements. The following are the minimum requirements for the displayed image as viewed from the viewing volume.

a. Field-of-View: Continuous 180-degrees, horizontal and 60-degrees, vertical.

b. Viewing Volume: 5 (lateral) × 3 (longitudinal) × 1 1/2 (vertical) feet with the bottom plane at the minimum pilot eye height and the forward plane at the maximum forward pilot position.

c. Geometric Distortion: Less than 5 percent throughout the field-of-view and anywhere within the viewing volume.

d. Collimation Error: Zero convergence to 4 milliradians divergency.

e. Resolution: 6-arc minutes, center, 8-arc minutes corner; assuming three 1000 scan line and 1000 television line resolution television inputs.

f. Highlight Brightness: 6 footlamberts.

g. Brightness Variation: Less than 25 percent over the entire field-of-view.

h. Contrast Ratio: 20:1, assuming 25:1 from the television input.

i. Joints: If the display is mosaicked, less than a 30-arc minute gap in the imagery.

j. Image Registration: If the display is mosaicked, the discontinuity of the image across a joint shall be less than one degree when viewed within the viewing volume.

k. Color: The optics shall be color corrected with minimal color shift and minimal color variation across the field-of-view.

l. Mapping: The system shall provide a linear image to the pilot using a linearity scanned television image input device.

Figure 2. Statement of Work

For instance, the IP would be located at the center, but to the rear of the aircraft commander and copilot, and, as a result, would see less vertical field. Panoramic scans by cameras inside B-52's and KC-135's, for instance, have shown for this condition that the field may be 20 degrees or less vertically. By the same token the vertical field is very much reduced for the aircraft commander or copilot when he looks through the distant or cross-cockpit side of the aircraft.

The concept of a graded field of view has been employed in some of the considerations of this report. The field at the front of the viewing volume has the full 180-degree by 60-degree requirement. At the rear of the viewing volume this has been reduced to 40 degrees vertically. For the pilot looking through the flight officer's window, the vertical field has arbitrarily been dropped to 30 degrees. The same, of course, is true for the flight officer looking through the pilot's side.

2.2.4 GEOMETRIC DISTORTION

The clarification given at an initial meeting between AFHRL and General Electric people in July, 1976, was that 5-percent distortion was to be interpreted as 5 percent of the vertical field or 3 degrees of angle. The design was based on achieving less than 3 degrees of distortion within the graded field of view discussed above.

2.2.5 COLLIMATION ERROR

It is desirable in a collimating optical device to keep the collimation errors small and on the divergent side. This means that all images in the field should appear to be located somewhere between a distant point in front of the observer and infinity. In these requirements, the angular divergence is 4 milliradians which involve the distance of the near point 625 inches, or -0.063 diopters.

In the design of collimating optics strict adherence to correction for infinite focus tends to make the errors vacillate about that correction such that both divergent and convergent conditions exist however small in magnitude. This is particularly true in the system of this study because of the many fringing-on-the-state-of-the-art requirements.

The subject of tolerance on convergence or divergence in displays has never been answered completely. In Puig (1973)[2], it is mentioned that the

[2] Puig, J.A., "Visual Tolerances for Simulator Optics," Proceedings of the Sixth Naval Training Equipment/Industry Conference, Nov. 13-15, 1973

MIL-HDBK-141, Optical Design (1962)[3] gives 17-arc minutes as the tolerance for all three—convergence, divergence, and dipvergence. Other tolerances cited in the same paper allow greater magnitude in divergence and as low as zero in convergence.

The display in this report has all three errors but they are generally of very low magnitude. Errors exceed the tolerance only in those parts of the field of view outside the graded-field concept.

2.2.6 RESOLUTION

Six-arc minutes center and 8-arc minutes at the edge is a realistic requirement. It is in the direction of upgrading current training devices' quality and is also compatible with improving technology.

2.2.7 HIGHLIGHT BRIGHTNESS

Six footlamberts is a good goal. It is modest by human factors considerations but completely consistent with existing technology. Many displays today operate at less than this value, in the 3- to 4-footlambert level.

2.2.8 BRIGHTNESS VARIATION

Less than 25 percent variation of brightness over the entire field of view is a difficult requirement to fulfill. One candidate television projection system for the purpose of this study, the General Electric Light Valve Projector, has a fall-off of greater than 50 percent. Actually the variation of brightness is not critical if the variation is gradual, but the edges between adjacent channel images must be very closely matched, possibly within 5 to 10 percent.

2.2.9 CONTRAST RATIO

The achievement of 20:1 contrast ratio with a 25:1 television input depends on the amount of scattered light that will be present in the low-gain, 180-degree-wraparound rear-projection screen in this report. Low gain is inherently associated with a high reflection factor. This suggests that special treatment such as use of black pigment must be used to lower that factor. The achievement of 20:1 contrast ratio could be a problem.

---

[3] MIL-HDBK-141, Optical Design, Military Standardization Handbook, Defense Supply Agency, Washington, D.C., 1962

2.2.10 JOINTS

A 30-arc-minute gap or less is certainly an end to strive for in a display such as this. No difficulties are contemplated in the approach of this study because of its nature.

2.2.11 IMAGE REGISTRATION

A one-degree or less discontinuity in the field is to be expected as a criterion in a display that is ideally intended to be continuous. There will be no problems due to this criterion because of the selected approach.

2.2.12 COLOR

Color matching between the multiple channels will be a problem for all systems although General Electric's Ground Systems Department has provided several juxtaposed displays to both industry and military, both collimated and non-collimated, in which this problem has been minimized by good color control.

2.2.13 MAPPING

It is required that the system provides a linear image to the pilot using a linearly scanned television input device. This implies that all distortion correction be done in the optical chain. The system of this report employs adjustment of the surface contour of one of the television projector folding mirrors to provide necessary pre-distortion to the rear-projection screen image.

A comment, however, might be in order. Because the simulator itself is the whole reason for this area of concentration and is the item most difficult to correct, it seems as though the predistortion might more simply be inserted into the CIG or the shape of the television scan lines. Then that distortion might be removed or just accepted in all the peripheral devices where the correction might be simpler. CRT monitor scans, for instance, can be modified to pre-correct the distortion. This was done in the Boeing displays produced by General Electric's Ground Systems Department.

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SECTION 3

TECHNICAL DISCUSSION OF PROBLEM AND APPROACHES

3.1 PROBLEM STATEMENT

There has been an increased emphasis on the use of simulators for pilot training and proficiency maintenance in recent years because of the rapidly increasing costs of operating aircraft. Furthermore, closer supervision and more precise performance measurement can be achieved with good simulators. The majority of training in simulators of the past has been, of necessity, limited to IFR operations because technology for visual displays was inadequate. Narrow field-of-view systems, which first made their appearance, incorporated television/modelboard for image generation and single-channel projectors on CRT's for display. These systems were acceptable for approach to landing but lacked the necessary field of view for extensive VFR maneuvering.

To generate images for wider fields of view, special television probes were developed with horizontal coverage of 120 degrees to 140 degrees for use on modelboard terrain flying. Additionally, television inset, and servoed/zoom lens cameras were perfected to generate television images for "Area of Interest" displays. Computer Image Generation (CIG) in the form of night-only "stroke-writers" and full day-night-dusk raster scan CIG has subsequently been developed. There is no theoretical limit to the number of channels CIG systems can generate. Television video signals for complete 360-degree spherical coverage in the form of mosaicked optical "windows" could be generated. Even signals for any size raster inset or superimposed image can be created by CIG.

The real problem is to produce a display system which can take full advantage of these CIG signals. Wide field of view, adequate brightness and realistic cockpit/scene orientation are required if valid training transfer is to occur. Several display systems have incorporated large domes with diffuse inner surfaces on which real images are projected. Such domes must remain fixed relative to the cockpit so that off-axis image distortion will not occur. General Electric overcame this problem on the 2F90 and 2B35 Visuals Systems which have floor-mounted screens around a motion platform. Pickoffs on the platform positions were fed to the CIG system so the image generated for the screens would correctly track the cockpit motions. Only limited pilot head motion can be tolerated or else the finite (short) distance between the cockpit structure and the image will become apparent. (General Electric has patented a "pseudo-infinity" display in which pilot's head motions are sensed and sent to

the CIG system to change image size and position to remove cockpit/image parallax errors.) In addition to completely eliminating this parallax problem, superior depth cues are realized if a virtual (infinity) image can be produced by the display. Success with very narrow field of view has been achieved with lens systems. Indeed, the collimated gun sight first used by the British in early World War II Spitfires and on all U.S. fighters since is a good example of this type of display. It has evolved into the HUD (heads-up display) with a relatively large field of view, and displays many parameters in analog and numerical form.

The most successful wide-angle displays for simulators have used reflective (mirror) optics. Among these are an in-line reflective infinity display and numerous mirror-45° beamsplitter displays. General Electric's Compu-Scene juxtaposed infinity display is a good example. The Compu-Scene juxtaposed display has a 30-degree vertical by 74-degree horizontal field of view and a 3-arc minute resolution but does not have the wide-angle image needed for aerial combat. It also does not provide large enough eye relief to accommodate everyone in a B-52 or KC-135 cockpit area simultaneously.

Another approach that uses an off-axis rear-projection screen and large surrounding mirror but no beamsplitters, has a large eye relief to accommodate the major area of a transport-type cockpit but only covers a total field of view of 38 degrees vertical by 50 degrees horizontal.

The in-line reflective infinity display applied to ASPT provides good angular coverage in azimuth and elevation and provides a collimated image for correct parallax cues with respect to the cockpit structure. It is too small, however, for a transport cockpit, and it does not have adequate image overlap between adjacent optical channels so that image gaps appear for other than moderate head motion. Furthermore, it is optimized for monochromatic light.

Several problems must be faced in developing the wide-angle, multi-viewer, infinity optics display called for in this study. To provide the 60-degree by 180-degree infinity image to the specified 5 feet by 3 feet by 1-1/2 feet viewing volume without cutting cockpit structure requires much larger optics than have been used heretofore. Careful analysis of layouts with tradeoffs between image resolution, image quality, number of projectors, number of CIG channels, size, weight and other such critical factors must be made to derive the best solution to this problem. To perform this study, there must be a thorough understanding of the technical and practical aspects of the contending display system and elements as well as the capabilities and performance penalties of the image generation and high brightness television projection systems. Since the display is to be mounted on a high-performance motion platform, structural and fabrication problems must be given full consideration in the design.

3.2 PRINCIPLES AND TECHNIQUES

3.2.1 GENERAL

The basic problem when viewed in its most simple form is to provide two functions: (1) creating an "infinity image" which subtends an angular coverage of 60 degrees V by 180 degrees H, and (2) providing a large enough window in the optics path to be able to observe this infinity image in total from anywhere in the 5 feet by 3 feet by 1-1/2 feet viewing volume prescribed. In this section, various approaches will be considered so that the rationale for selecting the most promising approach can be understood.

3.2.2 REFLECTIVE VERSUS REFRACTIVE OPTICS

Displays such as required may be broadly separated into reflective and refractive (lens) types. Because of the large size and large angular coverage required, the refractive system can be ruled out fairly quickly. An optical system with only a few projection channels is a necessity to minimize extra image area for scene overlap. A single lens per channel would be much too thick, and Fresnel lens (and macro variations thereof) are too expensive and impractical for many reasons. Furthermore, the necessary wide-angle lens would exhibit severe chromatic and spherical aberrations. A quality wide-angle image with the desired wide-eye relief angle simply cannot be produced with any form of lens array.

Reflective systems, on the other hand, have fewer inherent problems and can be made more efficient. They have a proven record and have been produced in various configurations and sizes.

3.2.3 IDEAL REFLECTIVE SYSTEM

After analyzing the requirements of this system, the "ideal" configuration for the reflective system can be deduced (see Figure 3). It would consist of a continuous spherical source image surface covering 180 degrees H by 60 degrees V. This would be located concentrically at the focal surface of a spherical mirror of twice the radius, also 180 degrees H by 60 degrees V. By employing a continuous real image at the focal surface, a full coverage, infinity image is generated (with no gaps) for every point in the viewing volume.

In order to reduce spherical aberration to a minimum, these two spherical surfaces would be as large as possible with respect to the 5 feet by 3 feet by 1-1/2 feet viewing volume (which must be centered laterally and lie entirely ahead of the common center of curvature of the spherical surfaces). A means must be provided for projecting the image undistorted to the screen with a minimum number of projectors, and some provision must be made for allowing the viewers to see through the screen.

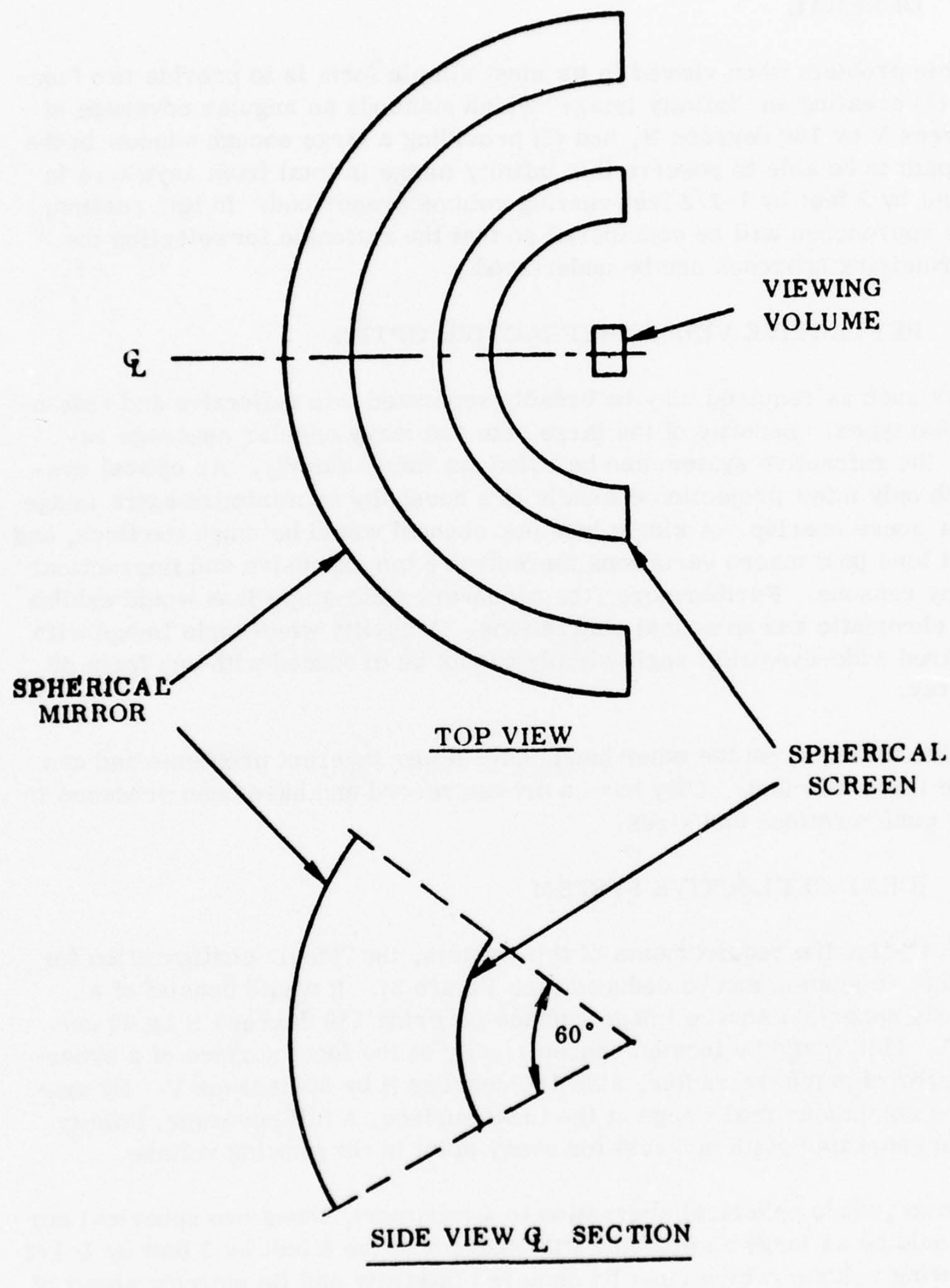


Figure 3. Ideal Reflective System

It should be noted that although this ideal configuration does not suffer chromatic aberration, it will have spherical aberration. However, because the pupil diameter of the observer's eye is small relative to the optics dimension, this aberration is interpreted by the eye as image distortion rather than image blurring traditionally associated with spherical aberration. Since rays from a point on the source image screen do not all reflect from the spherical mirror in a parallel bundle of light rays, the virtual image of this point will appear to shift in direction and "swim around" as the observer moves his head from one extreme of the viewing volume to the other. An idea of the magnitude of this effect is given in Table 2.

Table 2. Magnitude of Distortion Error

Eye Distance Off-Axis in Terms Of Mirror Radius	Distortion Error
Radius/8	-0.11°
Radius/4	-0.86°
Radius/2	-6.21°

The only way to correct perfectly for this is to incorporate a thick spherical lens concentrically located between the source image screen and the mirror. Such an element would be far too heavy, expensive and otherwise impractical to consider for this display.

The source image can be pre-distorted (by projection optics, raster sweep electronics, or CIG system) so that the view for any one point in the viewing volume is correct. This may distort the final image worse for other points; however, if all points of the viewing volumes lie off-axis in the same direction, some "average" predistortion can be applied. In any event, it can be seen that for best results the mirror radius should be large relative to the viewing volume to minimize image distortion.

3.2.4 PRACTICAL VARIATIONS

In the practical reflective system, the real source image (CRT face, etc.), must be located so as not to obstruct the view of the infinity image from any point in the viewing volume. This can be accomplished in two ways: (1) by using a flat beamsplitter to reflect the source image as a virtual object at the mirror focal surface, or (2) by physically offsetting the image source and the observer and operating in an off-axis mode. The characteristics of these two approaches will be briefly considered in the following paragraphs

a. Beamsplitter Approaches—The two familiar beamsplitter types are: (1) the "45-degree" type (such as the single unit General Electric Compu-Scene), and (2) the in-line reflective infinity display. In

both cases, the use of a flat beamsplitter and the geometry makes it impossible to use a single optical channel with 180-degree coverage. Because of this, a determination must be made as to the number of optical channels required, and what provisions must be made to prevent image gaps between channels.

In a system that uses the "45-degree" beamsplitter, it is conceivable that three juxtaposed units could be designed to cover the 180-degree horizontal field of view with adequate overlap to eliminate image gaps. However, such systems have a physical limit of the field of view in the vertical plane (i.e., in the radial plane perpendicular to the beamsplitter). Because the real image surface (CRT face, etc.) must be imaged on the mirror's focal surface (at R/2), it cannot be physically located far enough away off-axis to allow a full view of the 60-degree window when the eye is located at the center of curvature point (see Figure 4). The infinity image does cover 60-degree vertical by virtue of the size of the image screen relative to the mirror (i.e., it subtends 60 degrees), but the full 60-degree image cannot be observed simultaneoulsy unless the eye point is moved as close to the useful window (mirror) as point A. With the eye at this point, however, the distance to the two other juxtaposed window (mirror) sections is by geometry greater than that to the one being considered and a portion of this infinity image will be cut off in each. Thus, there is no position from which the observer can see the full 60-degree vertical coverage simultaneously through all three windows. The best vertical coverage which can be obtained around the 180-degree azimuth simultaneously (i.e., from the region of the center of curvature) is a little over 30 degrees. Thus, to provide adequate coverage two tiers of displays will be required, or a minimum of six units to cover the 180-degree by 60-degree area. Practical considerations of overlap requirements and resolution may increase this count to 8 juxtaposed units. One typical configuration analyzed required 112 degrees of infinity image to provide adequate overlap for a nominal 60-degree horizontal viewing window. Because the light must encounter the 50-percent reflective beamsplitter twice, the maximum theoretical efficiency would be less than 25 percent.

The ASPT application used pentagonal windows which could be circumscribed by a circle of about 75-degrees diameter, and it appears reasonable that with a little effort the design could be modified to a 60-degree by 60-degree rectangular format. The required 180-degree by 60-degree field could be covered by three such windows.

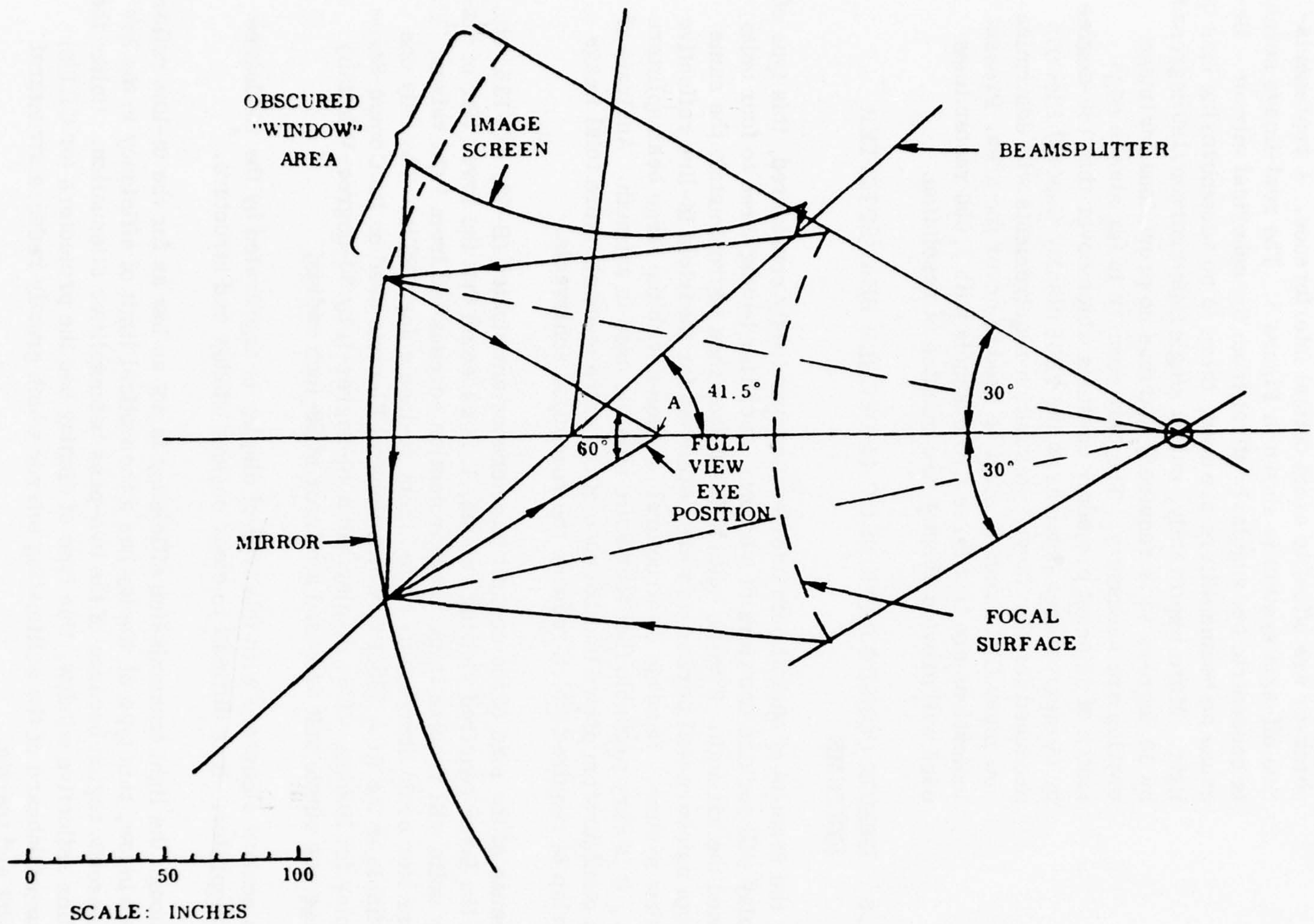


Figure 4. 45-Degree Beamsplitter Approach

b. Off-Axis Approach—In this scheme, the real image source and the observer are offset to avoid optical interference. A representative off-axis system is shown in Figure 5. The real-image screen is concentric but angularly offset from the spherical mirror. Because no beamsplitters are used, there is no accompanying loss of light. More importantly, only a single image screen (180 degrees H by 60 degrees V) is required, and thus no provisions for image overlap are necessary. The only concern is for simple edge match of adjacent projector channels which cover this 180-degree by 60-degree area (such as in the 2B35 display General Electric produced for the Navy). Resolution requirements will determine how many CIG channels must be used to cover the area. Present indications are that three CIG channels with 1,000 raster lines each will provide about 4-arc minutes of resolution.

3.2.5 DESIGN CONSIDERATIONS OF 45-DEGREE BEAMSPLITTER SYSTEMS

For the reasons of optical path interference previously considered, this type of display will require two tiers of windows, each tier having three to four units around the azimuth. If three units will suffice, then approximately the same design numbers will pertain as were developed for the triple in-line reflective window system. Because of structural problems with the large beamsplitters etc., it is very probable that four units must be used in azimuth. Analysis of this configuration shows that because of the extra channel, more total image overlap is required which reduces the resolution achievable.

Because of the size of the cockpit interference anticipated (B-52, KC-135, etc.), and the large required viewing volume, it is expected that the lower tier of display units will require large rear-projection screens fed from light valves. The upper tier could conceivably be fed from 26-inch color CRT's. The only one available is the RCA 1908P22 which General Electric used on its Compu-Scene display for Boeing. This display had a 40-degree-H by 30-degree-V infinity image per single unit and used a mirror of 59-inch radius.

The cockpit clearance with this type of display is aggravated by the 45-degree beamsplitter. It is difficult to clear cockpit window and structure.

Although the light transmission efficiency is not as low as for the in-line reflective window, this type of display has a theoretical limit of efficiency in the low 20-percent region because of the two-pass beamsplitter attenuation. Unlike the in-line reflective window, this type of display has the projectors (or CRT's) mounted inboard of the collimating mirror which greatly reduces structural weight and inertia.

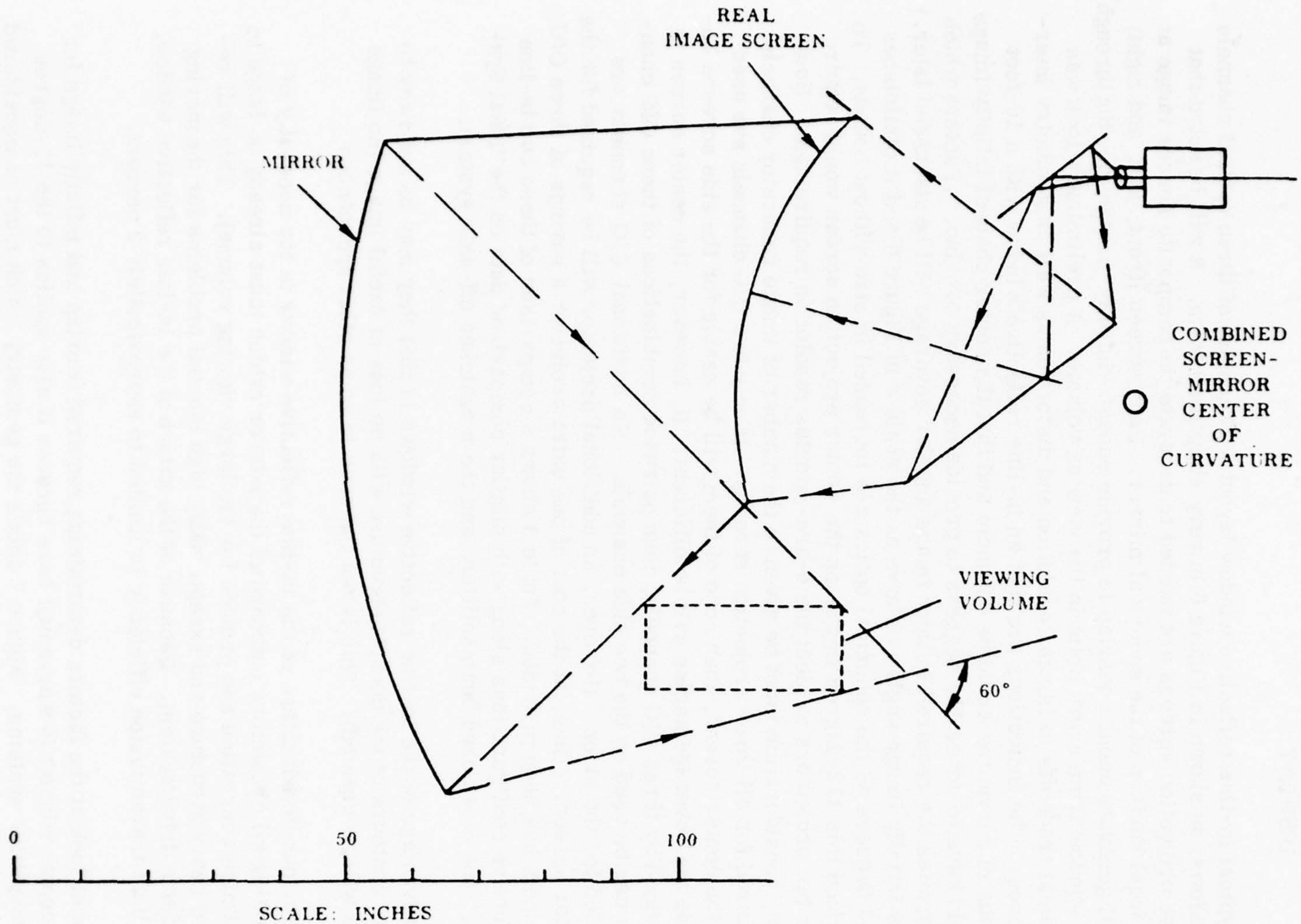


Figure 5. Off-Axis System

3.2.6 DESIGN CONSIDERATIONS OF IN-LINE REFLECTIVE WINDOW DISPLAY

A typical in-line reflective window layout will consist of three optical channels (windows) as shown in Figure 6 in very simplified form. It will be noted that three projection screens are needed to generate the composite source image at the focal surface of the spherical mirror. Each screen (front, left, and right) must generate enough overlap to provide enough "infinity" image viewing through any window from every point in the viewing volume. A preliminary look was taken at tradeoffs in image resolution and distortion as well as geometry interference. The indications are that an in-line reflective window with a 10-foot radius of curvature would be optimum and that the center channel infinity image would have to cover 112 degrees to provide necessary overlap. (Factors which determine the required infinity image angular coverage will be discussed later.) This infinity image angle is shown as the angle ψ in Figure 6 and it diminishes to 60 degrees as the spherical optics are increased in size without bounds. To produce this 112-degree image on the center projection screen would require only two projectors to meet the 6-arc-minutes resolution requirement. However, consideration must be given to the number of image generator channels required for all three projection screens. If only two CIG channels are used for the center screen, then none of them will be usable for the side screens because the coverage angles will be different. If, however, the center screen is serviced by three CIG channels, then pairwise combinations of these CIG channels can be used on the two side channels. No additional CIG channels are needed for the sides. However, an additional projector will be required for the center screen. Thus, at the cost of one extra projector a savings of three CIG channels has been provided. Table 3 shows a comparison of these two in-line reflective configurations along with similar comparison data on the "Ideal System," the mosaicked beamsplitter, and the mosaicked off-axis system.

An advantage of the in-line reflective windows is that they may be cut away to clear contours of the cockpit structure with no loss of useful image (no image gaps will be created). This is not the case in some other approaches

An obvious disadvantage of the in-line reflective window is the necessity of mounting all projectors outboard of the mirror (which must already be large to minimize aberration and provide for the large viewing volume). This will require heavy structure and exceptionally high inertial problems for the moving platform drive system. Because of the nature of the in-line reflective window, net light transmission efficiency is limited to approximately 2 percent.

A brief look at the factors determining required overlap and infinity image for the center window is warranted here because it also applies to the 45-degree beamsplitter systems. Figure 7 shows the geometry which must be considered for any such system with three windows in azimuth. The worst cases for viewing the infinity image are from the front corners of the 5 feet by 3 feet by

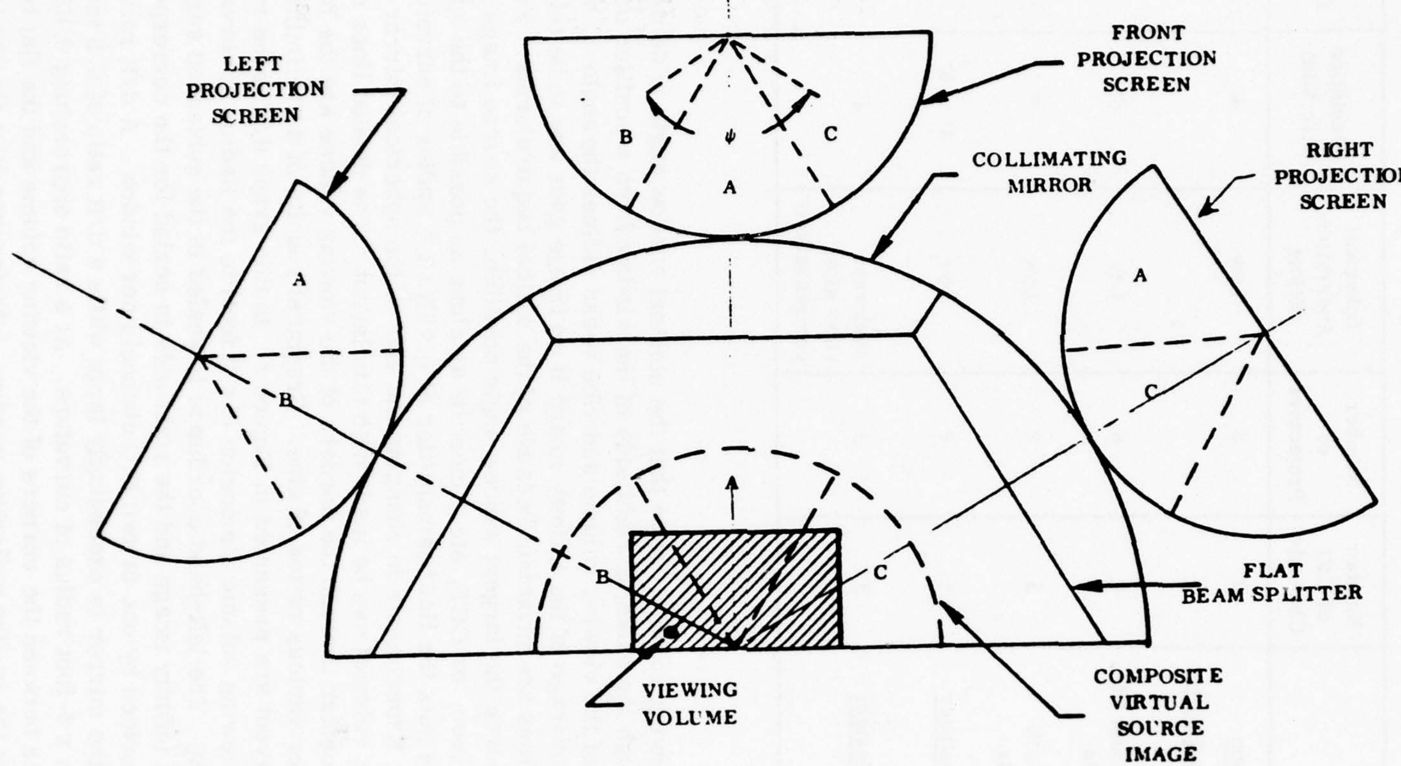
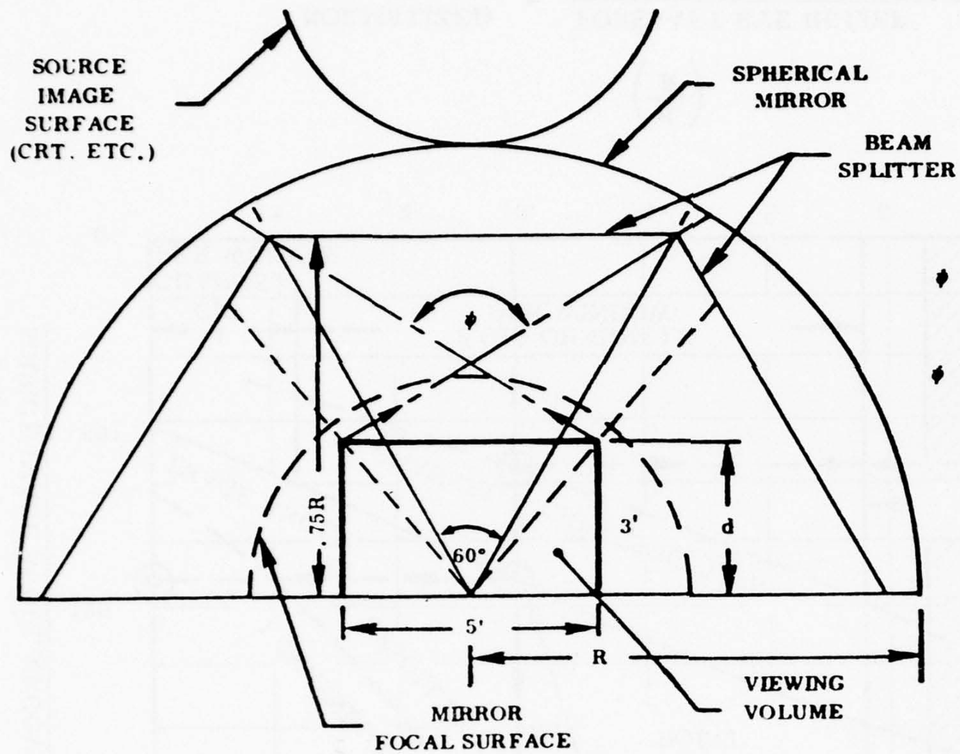


Figure 6. Multi-Viewer In-Line Reflective Window Layout

Table 3. Characteristics of Candidate—Wide Angle, Multi-Viewer Infinity Display Systems

	Number of CIG Channels	Number of Projectors	Spherical Aberration Effect	Resolution (Arc Min)	Light Transmission Efficiency
Ideal System	3	3	Low	4'	High
In-Line Reflective Window					
• Independent CIG Channels	6	6	Low	6'	Very Low
• Shared CIG Channels	3	7	Low	6'	Very Low
45° Beamsplitter Type	8	8	Low	4' to 6'	Low
Off-Axis System	3	3	Moderate (Low after compensation)	4'	Moderate

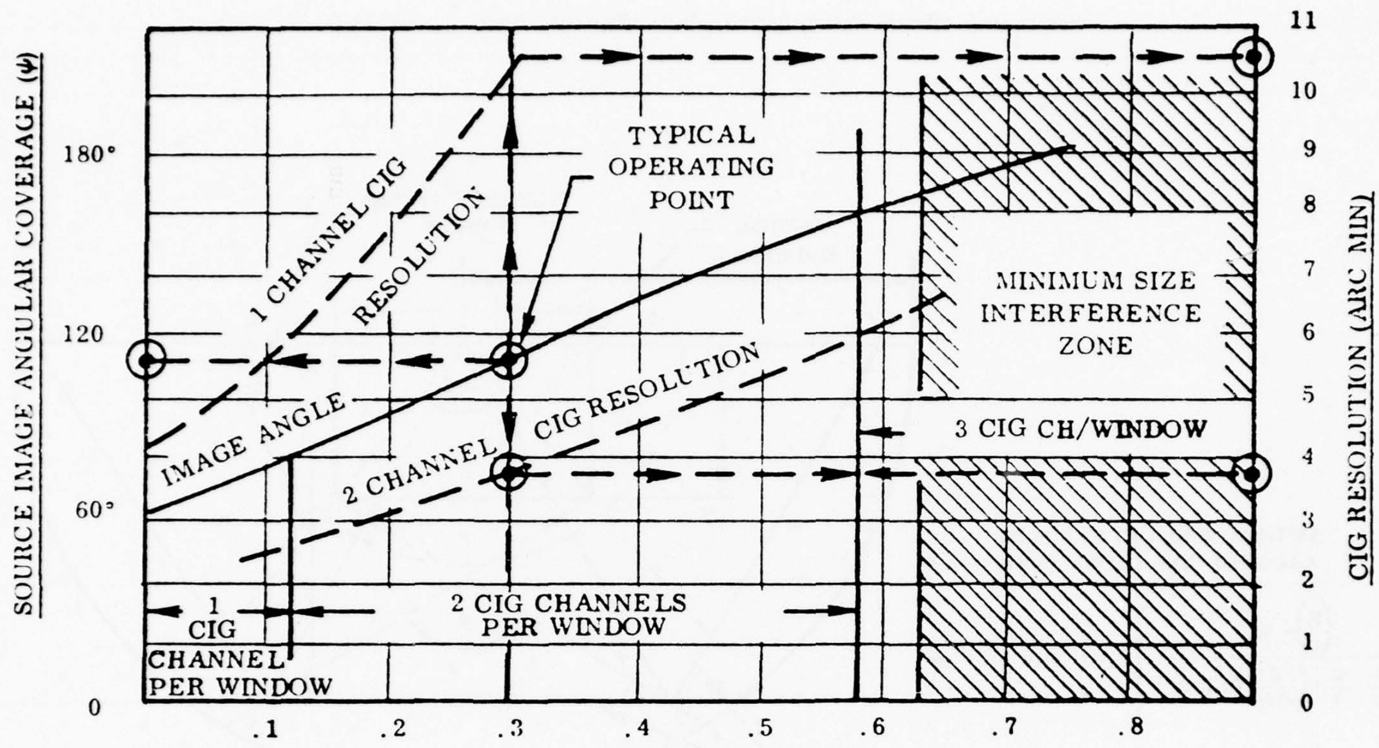
1-1/2 feet viewing volume. Note that the nominal window angle is 60 degrees. Looking through the extreme right side of the window from a position on the extreme left of the viewing volume and vice versa defines the angle ψ, which is the angular coverage of the infinity image if no image gaps are to be tolerated. Some dimensions are invariant because of the optical requirements. For example, to achieve the largest window angle possible, the source image surface (projector screen, or CRT, etc.) must be as close as possible to the spherical mirror. This puts the flat beamsplitter at 0.75R (R = Radius of curvature of the mirror). Experiments in changing the size of the spherical mirror (relative to the viewing volume) can be made with this layout. The dashed lines extending from the center through the corners of the viewing volume are the locus of the corners for various ratios of size. Graphical results of a preliminary analysis of this layout are presented in Figure 8. In this graph d/R is the ratio of the fore-aft viewing volume dimension (d = 3 feet) to the Radius of curvature of the mirror (R). The left-hand coordinate is scaled in the subtended angle required for the infinity image and the right side is scaled for the corresponding resolution provided by one or two CIG channels per window. A d/R ratio of 0 occurs when the mirror is exceedingly large while a d/R ratio of 0.5 identifies a mirror with a 6-foot radius of curvature. At a ratio approaching 0.63, there is interference between the corners of the viewing volume and the flat beamsplitter. (For the in-line reflective window, interference with the exit polarizer



$$\phi = 2\ \text{ARC TAN}\left[\frac{.75\ \text{TAN}\left(\frac{60°}{2}\right)+\frac{1}{2}\ \frac{5}{3}\left(\frac{d}{R}\right)}{.75-\left(\frac{d}{R}\right)}\right]$$

ϕ = MAX. ANGLE FOR INFINITY IMAGE IN CENTER DISPLAY

Figure 7. Determining Required Infinity Image Coverage



$$\left(\frac{d}{R}\right)$$

$$\text{NORMALIZED EYE RELIEF} = \frac{\text{FORE-AFT EYE RELIEF}}{\text{MIRROR RADIUS}}$$

Figure 8. Infinity Image Angle and Resolution Versus Ratio of Viewing Volume and Display

would occur before this point.) From the curve of single CIG channel resolution, it can be seen that an infinity image angle, ψ, of 80 degrees is the limit to keep within the 6-arc minute resolution requirement. This occurs at $d/R = 0.12$ and would require a hemispherical mirror of 46 feet in diameter. The typical operating point shown defines a 10-foot mirror radius and provides about 4-arc minutes of CIG resolution using two CIG channels per window. For mirror domes much smaller than this, the spherical aberration caused by the extreme off-axis geometry will cause severe image distortion.

3.2.7 DESIGN CONSIDERATION OF OFF-AXIS SYSTEM

The elevation layout of the off-axis system employs a spherical mirror tentatively of 12-foot radius. It is a continuous mirror (made up of sections) which wraps around the cockpit for the full 180 degrees by 60 degrees much like that of the "Ideal System." It forms the window through which the observers in the viewing volume will look at the infinity image. The input rear-projection screen has a radius of curvature of 6 feet and also covers the 180-degree by 60-degree format. Projecting onto the screen are three light-valve-type projectors such as those of the AFHRL high-resolution, high-brightness study or modified General Electric types. Each would ideally be located at the center of curvature, but they must be positioned further back by means of a folded optical path as shown. Necessary pre-distortion can be produced in the CIG, the television scan, or the surfaces of the folding mirrors.

Because of the exaggerated vertical off-axis position of all observers, there will be appreciable image distortion due to spherical aberration. The average value of this aberration can be compensated for by pre-distortion by either optical or CIG means. In the interest of economy of standardization, the CIG approach has much more flexibility for application to different cockpits (KC-135, B-52, C-130, etc.).

Another problem with this system is possible obstruction by the cockpit structure of light coming from the overhead screen to the spherical mirror. This can only be solved by careful layout with typical cockpit structures. Fortunately, the geometry is such that if this light path is accommodated, there will be no problem with the light returning from the mirror to the viewer other than the normal "real-world" obstruction by window frames, over-nose vision, etc.

Just as in the ideal system, there is no need for image overlap so that simple CIG adjacent channel edge match is all that is required. This does involve precision in alignment size, color and brightness, all of which General Electric has dealt with on the 2F90 and 2B35 systems. An automatic image size and alignment circuit on the latter system has proven highly effective. Because no overlap is needed, the resolution of this system will be much higher than for the beamsplitter types. With a proper layout, the off-axis system has the

advantage that none of its elements protrude into the cockpit volume. The avoidance of beamsplitters provides a large increase in light efficiency, but because of the off-axis arrangement, extra high-gain screens must be avoided. The initial look at this off-axis system indicates that although no large beam-splitters, etc., are needed, somewhat larger mirror diameter must be used. Because of this, there is a need for innovation in the design of the support structure to assure optical integrity under platform acceleration, yet achieve minimum weight and inertia.

3.3 SELECTED SYSTEM

Based on the previously discussed considerations, the off-axis system has been selected as the best from the overall system point of view. It uses the fewest CIG channels, has the best resolution, has the highest light efficiency and employs the least amount of large optical elements. The preliminary design indicates a 24-foot mirror but further refinement with typical cockpit layouts could significantly reduce this. It should be pointed out that the other approaches considered would also require very large "dome" mirrors because of the multi-viewer, wide-angle requirement. Large mirror sections with requirements similar to those needed have been manufactured. One vendor has produced in the past decade a number of mirrors of up to 23-foot diameter with a slope error of no more than 6-arc seconds.

Other than careful attention to vertical clearance for light path, the principal problem for the off-axis approach is in structural design and in getting the projected images to the hemispherical screen. As was discussed previously, the projectors can be mounted radially behind this screen with folded optics. Full advantage will be taken of the possible use of crossing light paths (for which no interference occurs) in selecting the optimum position of these projectors. The folding mirrors or optical relay system can also be used to predistort the image for spherical distortion at the average viewer position.

In short, an analysis of Table 3 will quickly indicate the inherent advantages of the off-axis system. It compares very well in all areas with the "Ideal System" used as a design yardstick.

SECTION 4

DESIGN AREAS OF CONCENTRATION

It was concluded in Section 3 that the off-axis system represents the best approach to a design that would most nearly satisfy the requirements of the study. Figure 5 is a typical cross-section of a system of this description.

Consideration of the plan of design study that will be followed breaks the system down into several areas of concentration. The most natural and simplest approach is that of passing light bundles of the desired field angle and collimation from the viewing volume into the mirror and, after reflection, to their optimum focus in a spatial region which is later to become a rear-projection screen. This effort represents the first area of concentration and might be called the display section. It involves the selection of a mirror configuration, size, and position based on virtues of acceptable imagery and feasibility of manufacture.

The second area of concentration begins with the image required by the mirror and goes on to the television projector array that will produce that image. This area, referred to as the projection section, includes the following considerations:

a. Amount and methods of producing required pre-distortion.

b. Rear-projection screen characteristics for satisfactory brightness and brightness fall-off.

c. Number and type of projectors needed to satisfy brightness and resolution requirements.

d. General layout of projectors and folding mirrors to conserve, save and distribute weight properly for motion platform needs.

The third area of concentration is mirror and screen fabrication methods. In that section methods for manufacturing the mirror and screen as described by various vendors will be discussed. Concern will be given for economy of manufacture and for ease of interfacing the components with the planned structural layout.

The fourth area of concentration is mechanical structure. This area is obviously concerned with packaging and providing structural integrity for the system units. It will explore regions of weight and space conservation, rigidity, simplicity in assembly and alignment, and ease of maintenance for the visual system components.

The described areas of concentration will be addressed in the next four sections. In general, each section will include a history of, or evolvement of the design approach for that section of the system It will then go on to a description of the final design/designs and a discussion of the expected performance for that area of concentration.

SECTION 5

DESIGN AND PERFORMANCE OF THE DISPLAY SECTION

5.1 INITIAL INVESTIGATIONS

The descriptions of studies that follow are written in chronological order. At times one study was interrupted in order to follow a promising lead that was not related to the study at hand. In other cases, where an apparent interruption occurs, the method of analysis was changed in the ACCOS V[4] ray-tracing program for some advantage.

The initial plan was to lay out a system having the general configuration of an existing off-axis system approach. It was then intended to increase its vertical field of view to 60 degrees and later to work into the 180-degree coverage in azimuth.

The first program was written at General Electric, Daytona Beach. It provided for ray-tracing a single spherical reflecting surface from the viewing volume to a series of flat vertical planes in the expected focal region. After establishing a position for the viewing volume, similar to that of Figure 5, one ray was traced from each of a group of eye points within that volume, all rays parallel, to the region of the investigative image planes mentioned above. The groups of intersecting points were plotted for each plane, and the best focal plane sought out.

The results of this study indicated that astigmatism was present, appearing as a vertically elongated image at the best focal position, and that imagery was best in the 30-degree-downward direction.

Because this optical program could handle only spherical surfaces the commercially available ACCOS V program was resorted to. ACCOS V is an interactive lens design and evaluation computer program designed for use in a time-sharing environment. It is available to the public via a national computer network. The

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[4] ACCOS V, Scientific Calculations, Inc., Rochester, New York

same type of program, with the vertical analytical planes in the region of focus, was employed very briefly for a sphere and an ellipsoid, both for vertex curvatures of close to 16 feet. The viewing volume in each case was located just below and slightly aft of the vertex of the screen position, very similar to that shown in Figure 5. The ellipsoid gave the tighter image spots but significantly greater distortion in the screen surface.

This method of doing the screen image evaluation with surface-by-surface plots of the point spreads was abandoned as being cumbersome. The ACCOS V procedure for doing a focal search for the spot diagram with the least root mean square (rms) radius was adopted as the most rigorous method of making the study.

The rms value of radius in a spot diagram is defined as follows:

$$\hat{R}^2 = .01 \sum_{j=1}^{N} W_j \left[(x_j - \hat{x})^2 + (y_j - \hat{y})^2\right]$$

where:

$W_j = K\, w_i/m_i$

and

i = index number designating the wavelength

W_i = spectral weight for that wavelength

M_i = number of rays successfully traced at that wavelength

K = normalizing factor to make the sume of ray weights for all rays in spot diagram add up to 100 percent

N = number of rays in spot diagram

$\hat{x}$ = x-coordinate of centroid of spot diagram relative to the reference ray point

$\hat{y}$ = y-coordinate of centroid of spot diagram relative to the reference ray point

x_j = x-coordinate of any ray relative to the reference ray point

y_j = y-coordinate of any ray relative to the reference ray point

$\hat{R}$ = RMS radius of spot diagram

The distribution of spots may take on any form depending on the aberrations present. In this application the distribution of spots is related to the distortion mappings that appear later in the report. Any deviation of one of the grid intersections in those mappings may be identified with a mispositioned spot in the spot diagram. The extent of the mispositioning is directly related to the deviation of the spot from the centroid of the spot diagram.

5.2 FURTHER INVESTIGATIONS

The study then took the form of assigning various conical shapes and sizes for the mirror and doing slight variations on the position of the viewing volume, still basically in the "Off-Axis System" location below the screen. Figures 9 through 12 illustrate four typical candidate systems. The object of the exercise was to provide for complete 60-degree coverage vertically throughout the viewing volume with no screen interference, and to evaluate image quality and distortion in the screen region. Complete 60-degree coverage was obtained as shown except in the case of the paraboloid. In that case strict adherence was made to the stipulation that the viewing volume be centered on the focus of the paraboloid to keep the chief rays within bounds and minimize spherical aberration. In all sketches the extent of the mirror is indicated by the upper and lower rays of the envelope for the viewing volume. Except for the double-size sphere the mirrors all have a vertical span of about 13 feet. Each figure also has the location of the screen image points for plus 30-, 0-, and minus 30-degree elevation. The distortion at the screen can be measured by the relative equality of spacing between 30 and 0 degrees, and minus 30 and 0 degrees. The spherical system is significantly better than either the ellipsoid or paraboloid in this respect. The paraboloid also requires a tremendously large screen, about 15 feet in height versus 9 feet for sphere and ellipsoid. All sketches show two encircled points in the +30 degree elevation position at the screen. These are two different foci for ray bundles from the viewing volume. One is for a ray bundle passing through an aperture in the front face, the other is for the rear face. The double-size sphere shows the best performance in this respect with both foci relatively close together. This, as well as better image quality of the points in the screen is to be expected for the larger spherical mirror because the viewing volume is relatively smaller in size for that configuration and therefore employs relatively smaller apertures.

The comparison of the four systems for image quality is given in Table 4. The measurement of image quality is the rms radius for the spot diagram. The data in Table 4 point out several facts. The paraboloid, despite its very bad distortion characteristics at the screen, provides the best image quality. The

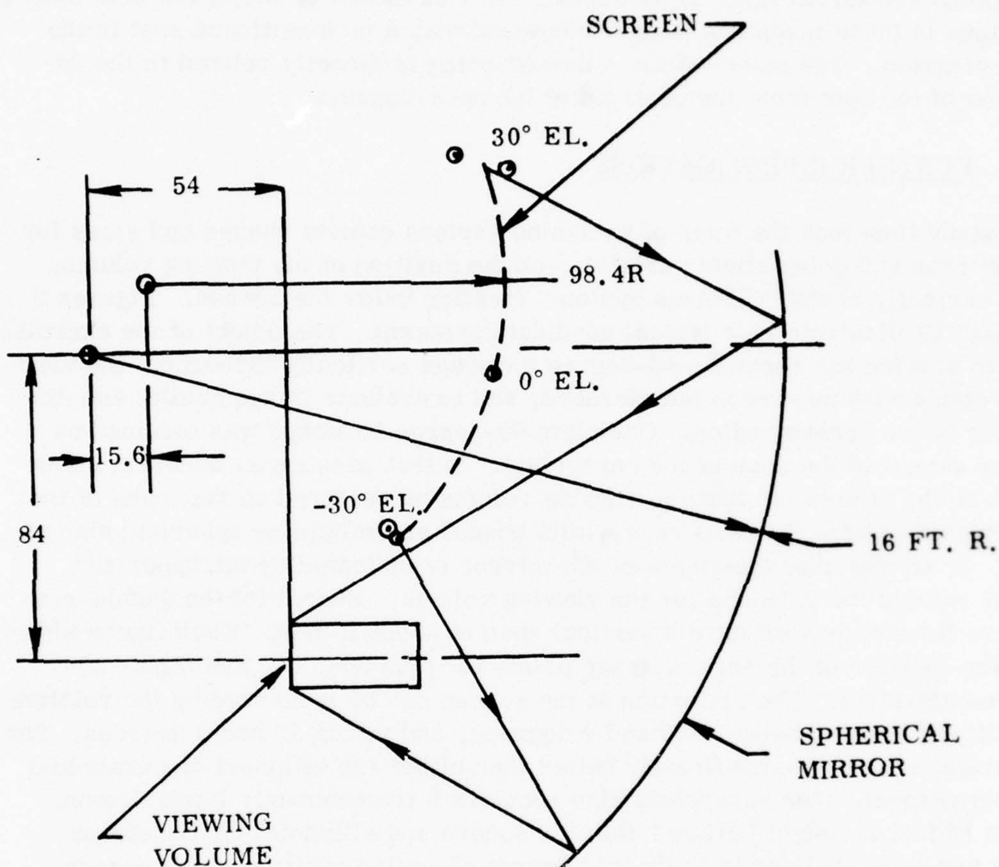


Figure 9. Preliminary Design with Spherical Mirror

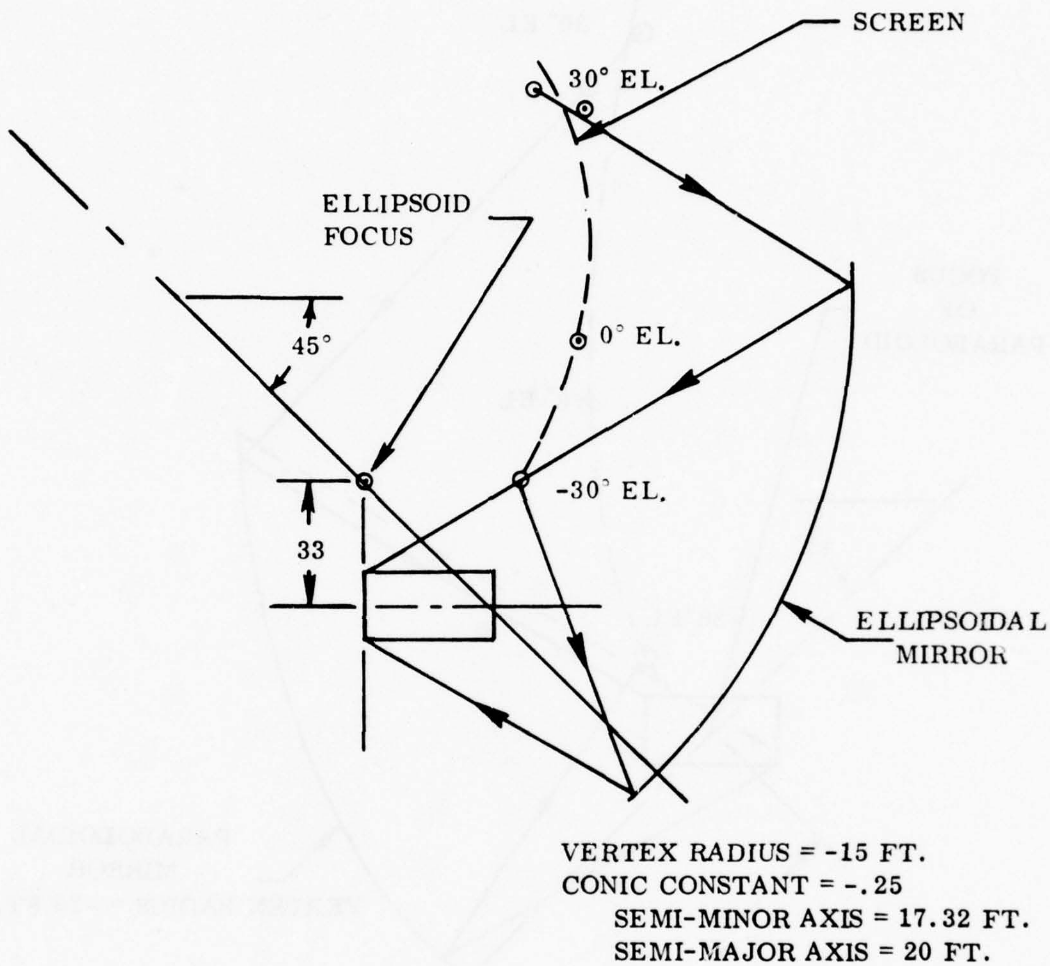


Figure 10. Preliminary Design With Ellipsoidal Mirror

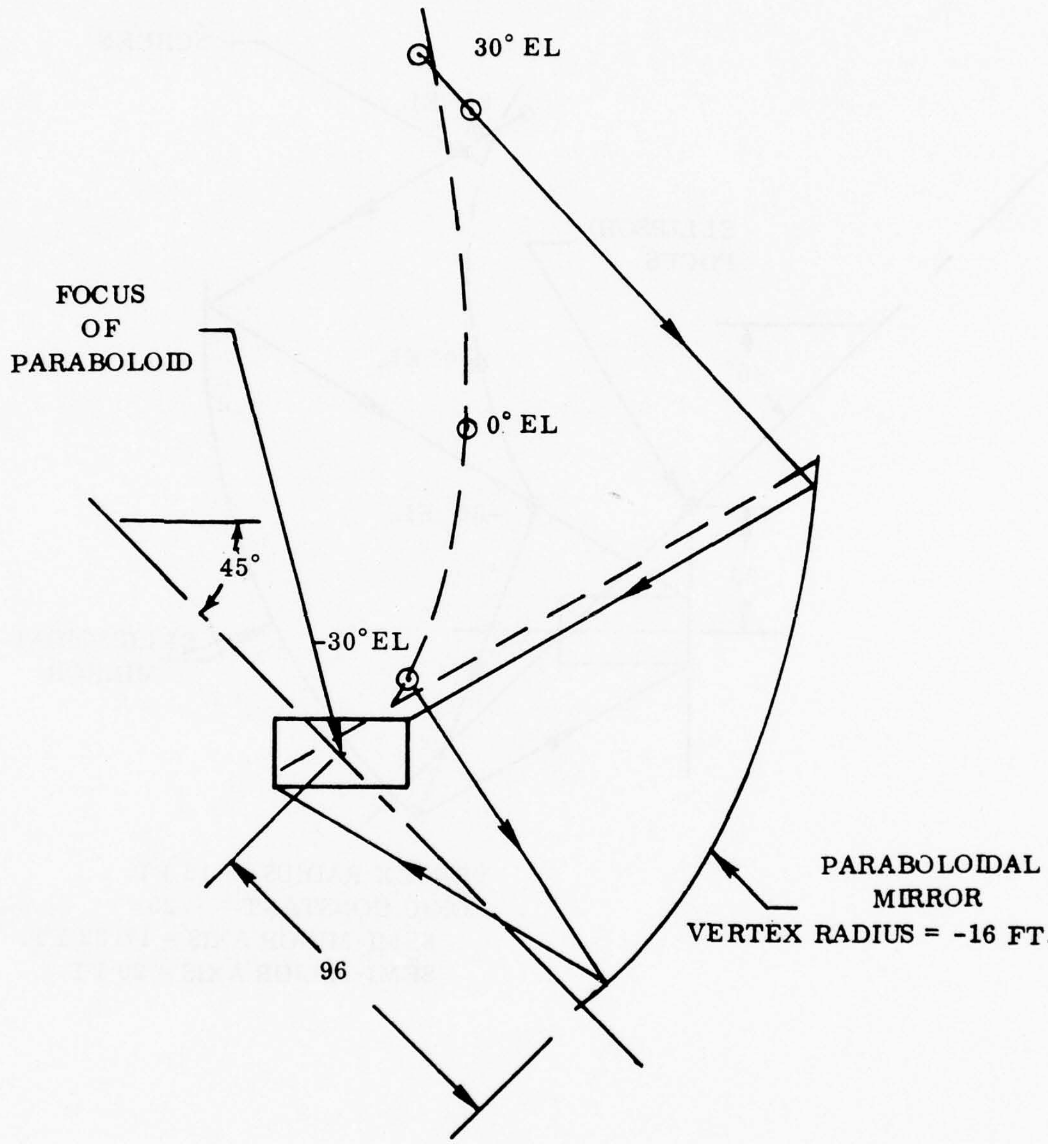


Figure 11. Preliminary Design With Paraboloidal Mirror

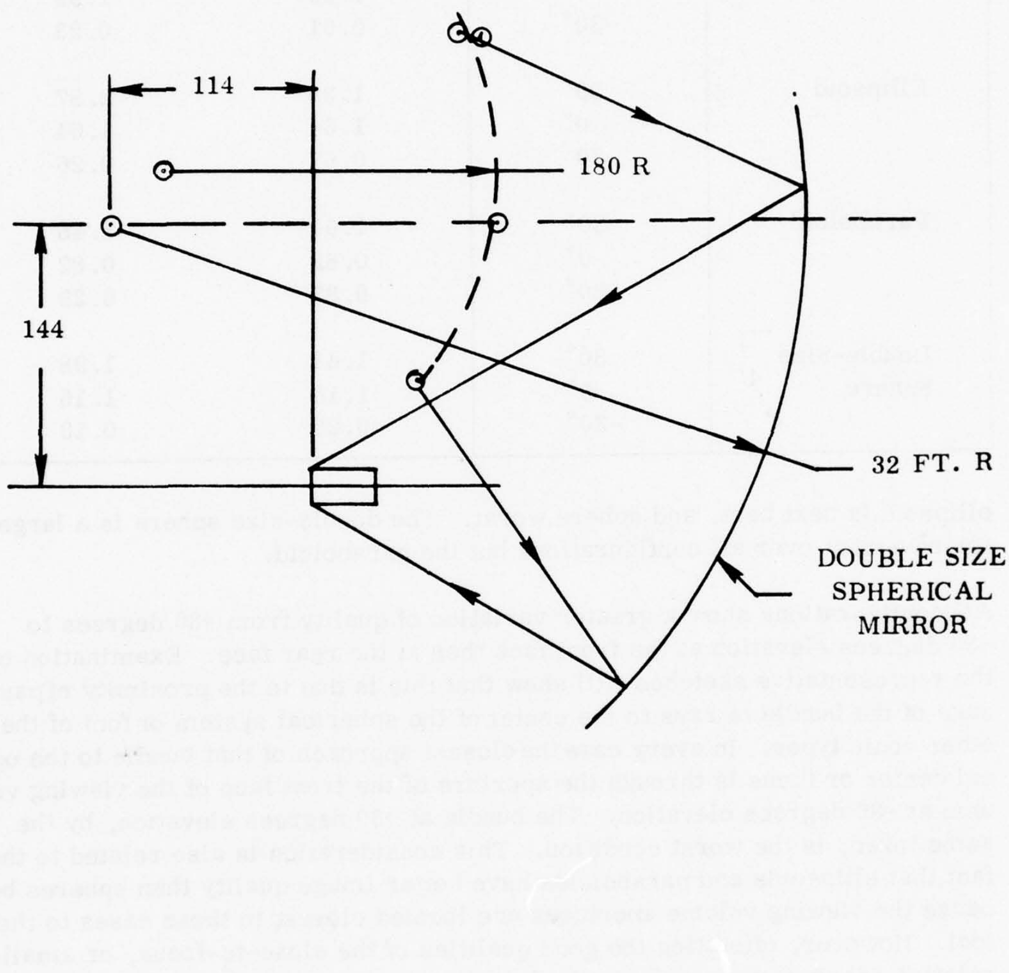


Figure 12. Preliminary Design With Double-Size Spherical Mirror

Table 4. Image Evaluation for the Optical Configurations of Figures 9, 10, 11 and 12

		RMS Radius (Inches)	
	Elevation	Rear Face Aperture	Front Face Aperture
Sphere	30°	2.09	3.77
	0°	1.99	1.99
	-30°	0.61	0.23
Ellipsoid	30°	1.38	2.87
	0°	1.64	1.64
	-30	0.67	0.26
Paraboloid	30°	1.04	1.45
	0°	0.82	0.82
	-30°	0.37	0.29
Double-Size Sphere	30°	1.48	1.98
	0°	1.16	1.16
	-30°	0.25	0.13

ellipsoid is next best, and sphere worst. The double-size sphere is a large improvement over all configurations but the paraboloid.

All configurations show a greater variation of quality from +30 degrees to -30 degrees elevation at the front face than at the rear face. Examination of the representative sketches will show that this is due to the proximity of passage of the bundle of rays to the center of the spherical system or foci of the other conic types. In every case the closest approach of that bundle to the optical center or focus is through the aperture of the front face of the viewing volume at -30 degrees elevation. The bundle at +30 degrees elevation, by the same token, is the worst condition. This consideration is also related to the fact that ellipsoids and paraboloids have better image quality than spheres because the viewing volume apertures are located closest in those cases to their foci. However, offsetting the good qualities of the close-tc-focus, or small relative aperture approach, is the fact that the ray bundles interfere with the rear-projection screen in those cases. This is obvious in Figure 11, for the paraboloid. The viewing volume is centered on the paraboloid focus but +30-degree upward viewing is also limited to the lower front portion of the viewing volume as shown.

5.3 DOUBLE ELLIPSOID SYSTEM

A system configuration which differs from the off-axis approach discussed in Section 3 was conceived early in the study and was analyzed in parallel with the above configurations. The rationale for this approach was that an aerial image located at the position of the real-image screen in Figure 5 would allow the viewing volume to be located nearer the center of curvature of the mirror, Figure 13. This location is the position of minimum aberrations for a concentric optical system; therefore, it was reasoned that lower distortion over the viewing volume could be obtained. The next step was to devise an approach to locate the image, keeping in mind that the image is probably nearly spherical and subtends 60 degrees by 180 degrees. There is also the requirement that a bundle of rays emanate from each point on the aerial surface in order to fill the viewing volume. Essentially then, a pupil is being introduced into the system making it a pupil-forming system. Since an optical component must be used to project the aerial image into the desired position, it is necessary that the projection component subtend a larger angle than 60 degrees by 180 degrees. Because of the large angles, the assumption was made that only reflective, not refractive, components could be considered. At this point, there are two approaches: Use one mirror to project the image, or use a group of mirrors to project a juxtaposed aerial image. It was assumed, but not proven, that a juxtaposed approach would result in the same instantaneous versus total field-of-view trade-off which leads to use of two or more projectors per 60-degree by 60-degree viewing channel to maintain adequate resolution. In order to avoid the use of more than three projectors total, the single-mirror approach was chosen. The basis of projection with a concentric mirror configuration is shown in Figure 14. This method has been used quite successfully in NASA simulator applications, Figure 15. As shown in this figure, 45-degree beamsplitters are used which again leads to the problem of multiple projectors per channel due to the juxtaposed optics effect on instantaneous versus total field of view as explained in Section 3. Also, this beamsplitter would become very large, making mounting difficult.

In order to avoid these problems, an off-axis projection configuration was chosen, which is analogous to the off-axis viewing arrangement. In summary, this configuration allows the viewing volume to be located in an area more nearly free of spherical aberrations and offers an additional degree of freedom for minimizing aberrations. That is, the analysis can consider three surfaces (2 mirrors and 1 screen) to optimize the solution instead of two (1 mirror and 1 screen).

The first problem to consider was whether the configuration could be adjusted to avoid blocking or losing rays. It was discovered early that the first mirror surfaces which should be considered were ellipsoids of revolution sharing one focus and having the same eccentricity. This type of system was considered in application to heads-up displays. It utilizes the conjugate foci principle, and is evolved from the Gregorian telescope. However, the conjugate foci principle

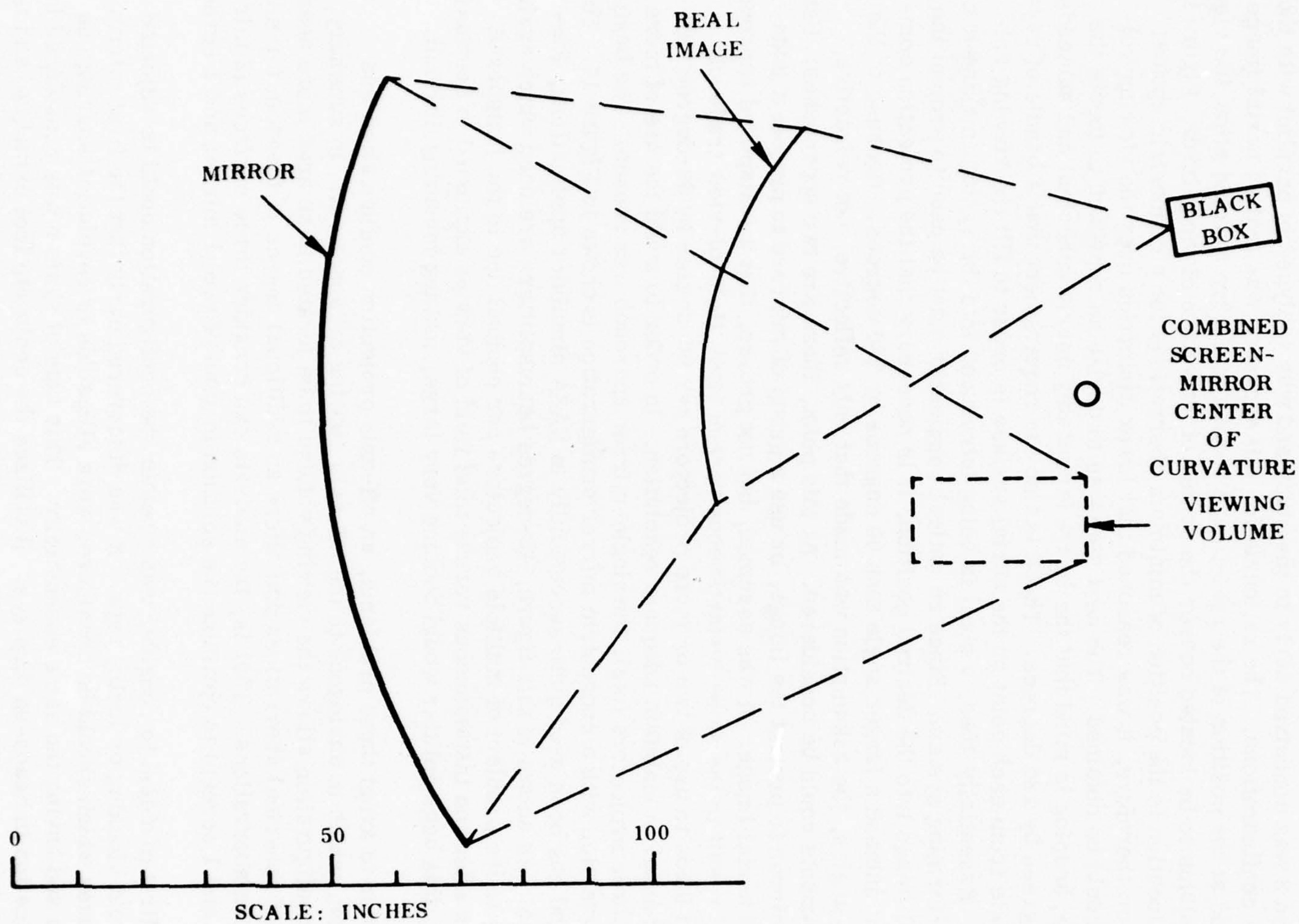


Figure 13. Off-Axis System With Real Image

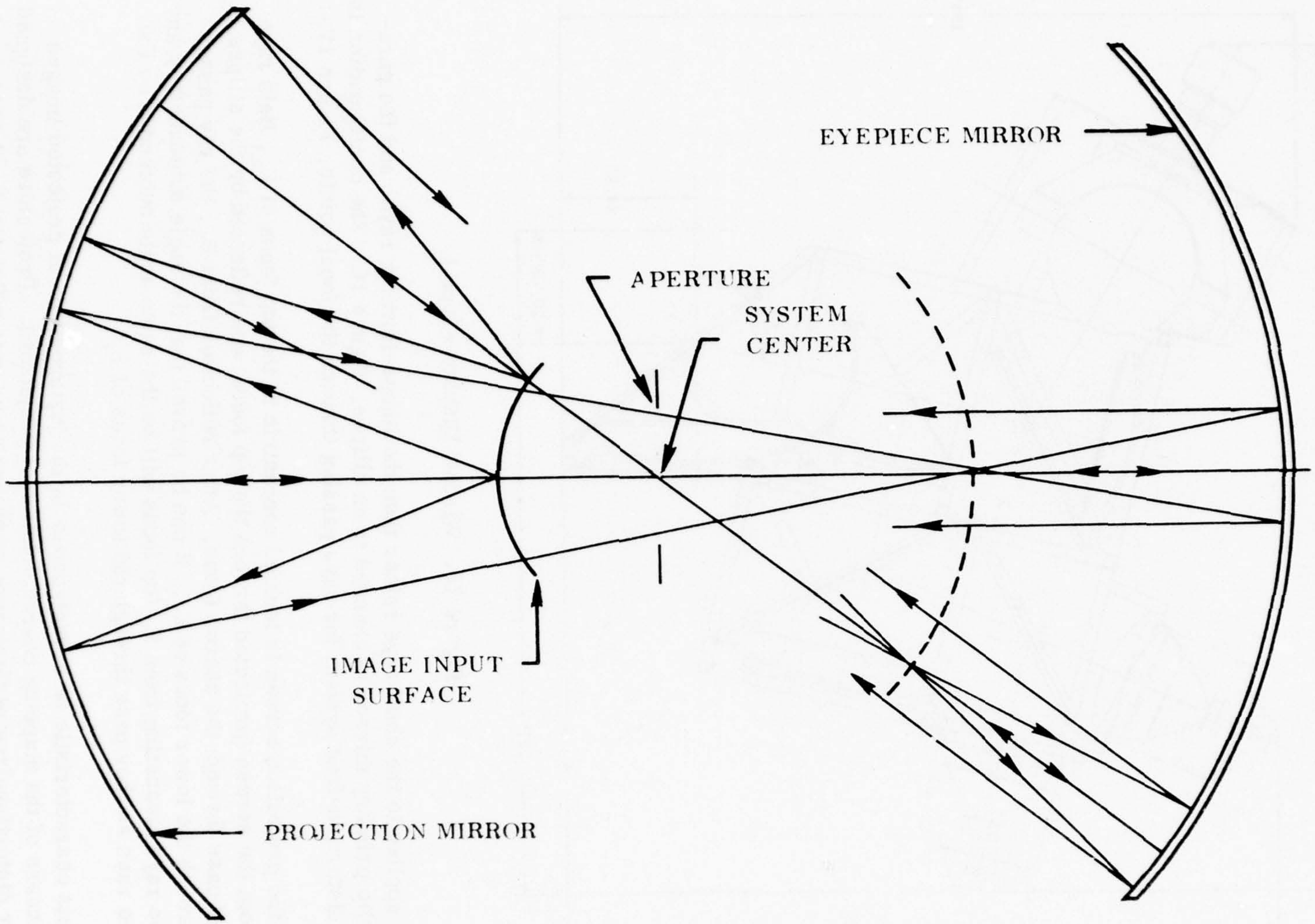


Figure 14. Basic Two-Mirror Display System

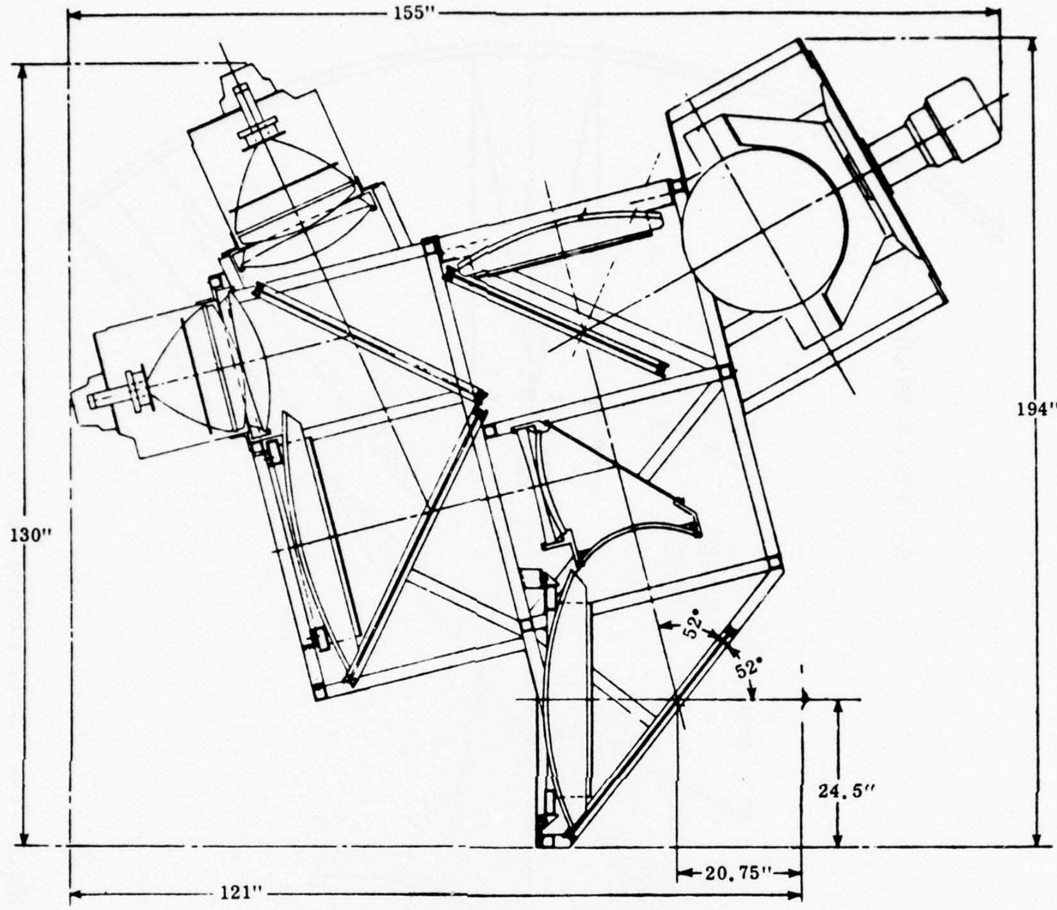


Figure 15. Window Display—Type I

is applied to the chief rays rather than the image-forming rays, and the parabolic primary mirror is changed to an ellipse, Figure 16. The configuration is a distortion-free system for rays passing through the focal points, Figure 17.

If the projection screen is located concentric to the top focus of E_2, field rays from the screen (projected through the top focus) are reflected by the ellipse E_2 and pass through the shared focus. After reflection from E_1, the ray passes through the lower focus of E_1. It can be proved that the angle subtended by any two rays emanating from E_2 top focus will be the same angle subtended by the two rays as they pass through the lower focus of E_1.

This characteristic is advantageous in the juxtaposition of projected images because of the mapping characteristics of projectors. Projectors are designed for distortion-free performance when projected onto a flat plane. Assuming that three flat planes each subtending 60 degrees by 60 degrees are tangent to

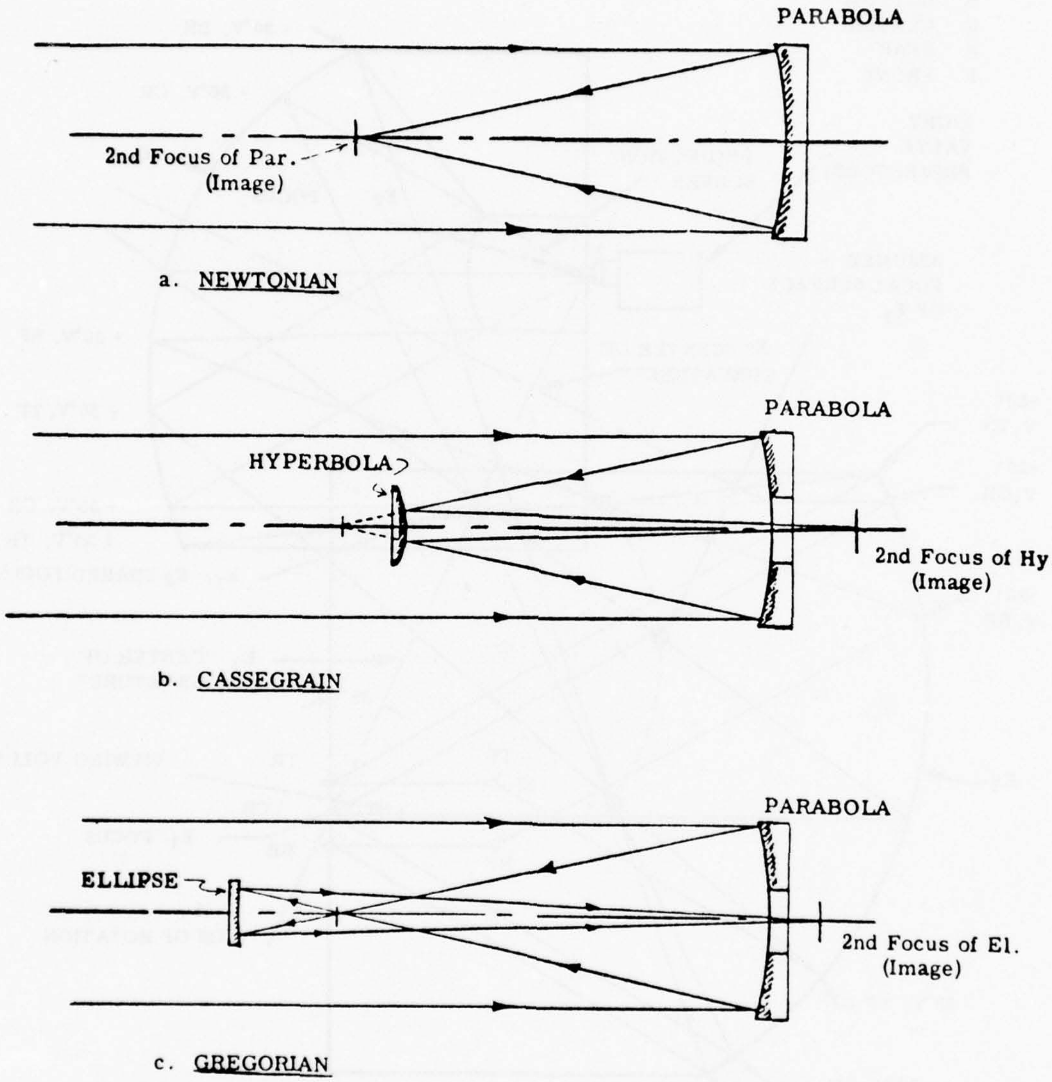


Figure 16. Basic Reflecting Telescope Designs

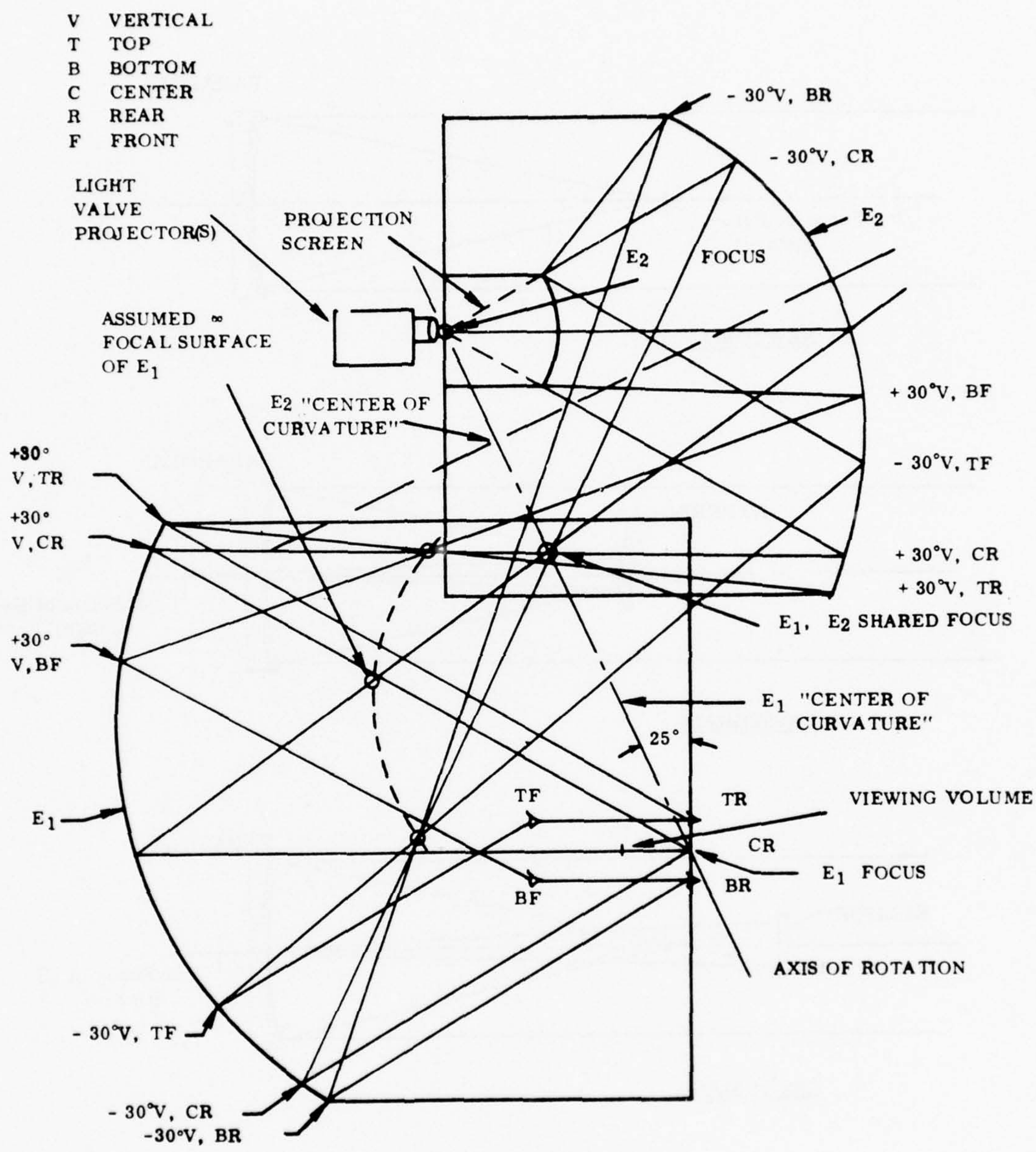


Figure 17. Double Ellipsoid for Simulation

the projection screen, the rays projected to those screens are intercepted by the spherical screen. The mapping of this system is distortion-free for computer generated images.

Several iterations of the double ellipse configuration were tried before arriving at Figure 17. In general, the problem was to find a combination of radii of E_1 and E_2, eccentricity, tilt of the axis of rotation with respect to the horizon line and placement of the viewing volume which would eliminate blocked or lost rays. Graphical analysis was used to find the configuration of Figure 17. The assumption was made that the aerial focal surface would be a sphere. Field rays were traced through the foci to find image points on this surface for a viewer located at the lower focus of E_1. These image points were assumed constant for the same field rays over the whole viewing volume. The projection screen was located from a first-order ray trace assuming E_1 was a sphere. Figure 17 indicates no rays are lost and the only rays blocked are in an area around +25 degrees elevation at ±80 degrees azimuth caused by an overlapping of E_1 into E_2. No further attempt at a graphical approach to elimination of the overlap area was made due to the first-order assumptions on location of the screen and its real image. At this point, the critical parameters are:

E_1	Mirror axis radius	=	12'
E_2	Mirror axis radius	=	9'
E_1	Foci separation	=	8'

Axis of rotation tilt from horizon = 65 degrees
Viewing volume has rear face centered on focus of lower ellipse

From this data, the vertex radius is 8'.

At this point, the configuration was analyzed via ACCOS V. Ray-tracing was done from the viewing volume through the mirrors to the screen. Rays from the front and back faces were analyzed as separate pupils. The centroids and the rms radius of the distribution around the centroid were calculated.

Table 5 lists the rms values at the aerial image for rays from the back or rear face of the viewing volume. The largest value is 0.89 inches which is equivalent to 0.7-degree angular deviation for the approximate 6-foot focal length of this portion of the system.

This result can be compared to Table 4. The rear face using an ellipsoid gives a deviation of 1.38/96 = 0.82 degrees. These data start to give a comparison of the one- and two-mirror systems. The performance in the forward direction is comparable if the radius of curvature of the one-mirror system exceeds that of the two-mirror system by about 50 percent. This was the anticipated result. Since the viewing volume is near the axis of rotation in the two-mirror system,

Table 5. Image Size at Aerial Image (Double Ellipsoid)

	Elevation	RMS Radius (Inches) Rear Face	RMS Radius (Inches) Front Face
Aerial Image	30°	0.24	—
	0°	0.47	—
	-30°	0.89	—

it can be assumed that the performance would be much better than the one-mirror system at large azimuth angles.

The data in Table 6 reverse these conclusions. The rms radius is much larger at the projection screen, which indicates that in order to satisfy the rms spot size and the ray directions at the aerial image, the rays must emanate from a large area at the screen. Reversing the process by assuming the rays are point sources at the screen results in an angular error of 2.95/33.6 = 5° for the rear face.

It is evident that the upper mirror, which provides a distortion-free condition for a viewer at the lower focus of E_1, does not function well over the large viewing volume. An even better illustration of this problem is shown by the calculated centroid locations shown in Figure 18. Notice the wide separations between the centroid locations for the front and rear faces of the viewing volume.

It is concluded that the double ellipsoid cannot be used because of the large variation of focus in the screen region for various eye positions in the viewing volume. A contributor to this difficulty, Figure 18, is the large numerical aperture of the light bundle approaching a focus at the screen at the top of the diagram. The rays making up this bundle are marked -30° V, BR; -30°V, CR; -30° V, TF.

5.4 CONTINUING ANALYSIS OF SINGLE-MIRROR SYSTEM

The original approach in producing a display for the Wide-Angle Multi-viewer System was to design an optical system which, in vertical cross-section, optimizes imagery. The vertical section was then to be rotated about a vertical axis to generate the 180-degree field in azimuth. The configuration chosen was the single-mirror, single-screen approach as exemplified by an existing off-axis display which is operable over a field of view that is much reduced from the requirements of this application. It appeared desirable in the design to employ spherical surfaces, if possible, in order to simplify manufacturing processes. However, for completeness, a series of conic sections of various

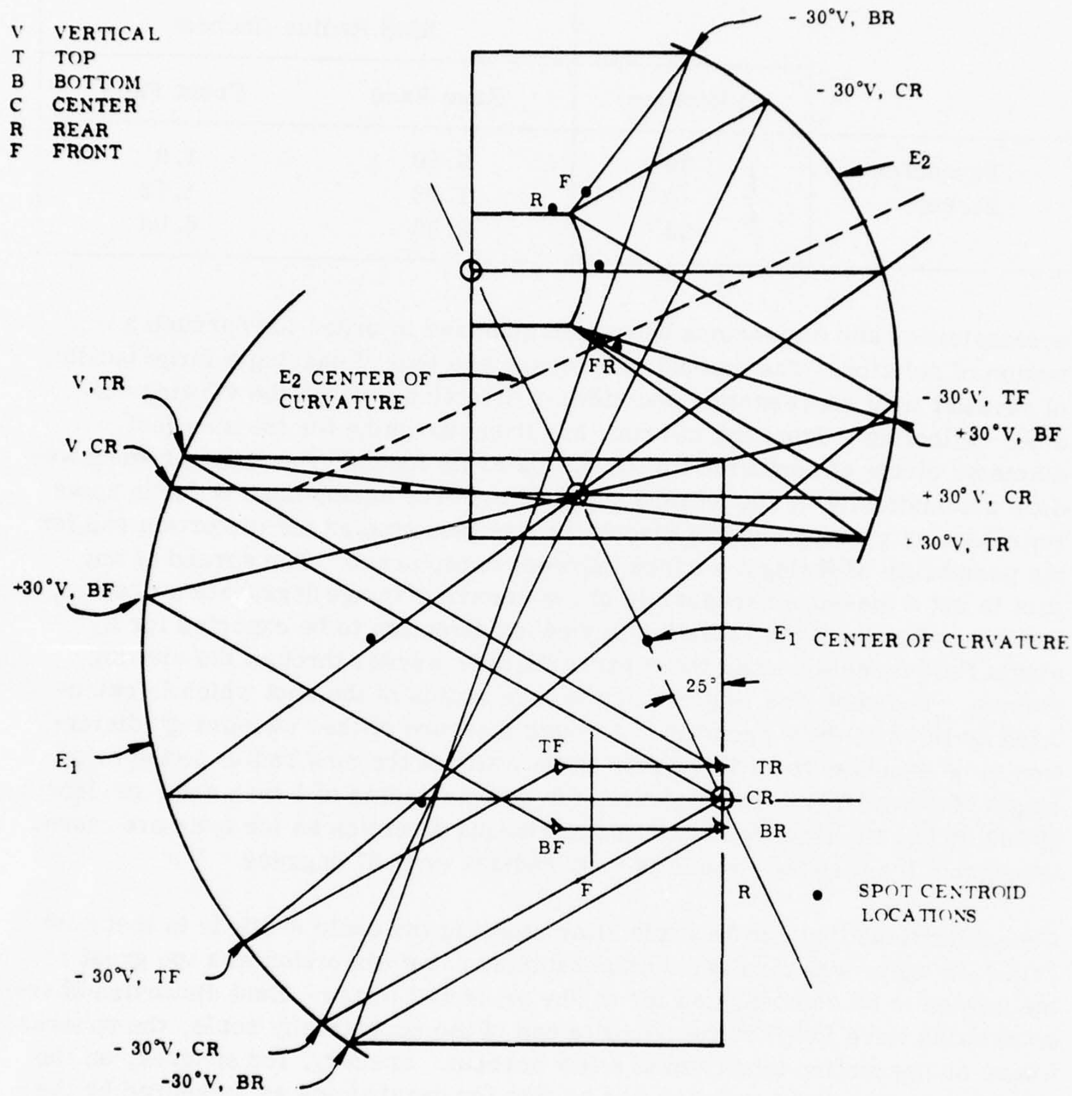


Figure 18. Actual Centroid Locations

Table 6. Image Size at Projection Screen (Double Ellipsoid)

	Elevation	RMS Radius (Inches) Rear Face	Front Face
Projection Screen	30°	0.89	1.0
	0°	1.78	1.78
	-30°	2.96	6.08

eccentricities and dimensions were also analyzed in order to approach a region of solution. The method of analysis was that of passing a large bundle of parallel light representing one viewing direction through the viewing volume, reflecting it from the mirror, and then searching for the smallest diameter circle of confusion for the bundle at its focus. The latter process was done automatically by the ACCOS V program. The assemblage of focus spots representing various viewing directions was then studied for distortion and for the possibility of fitting a surface (screen) to the array. The spread of any spot is not a measure necessarily of the amount of image degradation present, but is a measure of the variation in viewing direction to be expected for a single field direction when the observer's eyes wander through the viewing volume. The spot size is given by the rms radius of the spot which is calculated by the ACCOS V program. A rough measure of the "swimming" distortion to be expected from this cause is the ratio of the rms radius to the focal length of the system. For instance, for an rms radius of 1 inch and focal length of 100 inches the expected variation of viewing direction as the eyes are moved throughout the viewing volume is 0.01 radians or 0.57 degrees.

Generalizations that can be made after studying the conic sections is that best "rms" imagery was obtained with paraboloids, but distortion was too great at the screen to be compensated for in any projected image. Best distortion characteristics were found at the opposite end of the eccentricity scale, the spheres, where compensation amounted to a few percent. Imagery, for spheres, on the other hand, was about twice as bad as that for paraboloids as measured by the rms spot radius. In all configurations it was found that the array of image spots changed in space location and size depending on the aperture of the viewing volume through which the bundle of parallel rays was traced. Usually the analysis was done by using the rear and front faces of the viewing volume as separate apertures. An attempt to remove this anomaly was made by using an enlarged aperture at the center of the viewing volume which would include all rays that could possibly pass through that volume and cover a 60-degree vertical field. This invariably resulted in more poorly defined spots, of the order of 4 or 5 inches rms radius for a 100-inch focal length, which, being nearly 3-degree "swimming" error, was considered unacceptable.

5.5 OFF-AXIS ANALYSIS

It was now decided to investigate the off-axis properties of one of the above approaches. Up to this point all that had been analyzed was meridional imagery. The most improved spherical configuration was used for this purpose. Off-axis (in azimuth) bundles of parallel rays were traced through the front and rear faces of the viewing volume at 30 degrees and 60 degrees azimuth. Table 7 lists the results. One grouping in the table is the front face and the other the rear face of the viewing volume. The data may be considered as comparative numbers in which those numbers associated with the same azimuth and elevation angles should be ideally the same for either focus (z), y, or x. Of greatest concern are the variations of x values which means that a horizontal distortion of up to 30 inches must be impressed on the image projected onto the screen. This distortion is absent for 0 azimuth as can be seen by the columns of 0's under x for that direction.

Table 7. Locus of Image Points for Off-Axis Imagery for Spherical Nonrotationally Symmetrical System

Front Face (Locus in Inches)									
	Focus (z)			y			x		
El/Az	0°	30°	60°	0°	30°	60°	0°	30°	60°
30°	-4.84	-4.70	-3.45	53.23	53.20	52.11	0	-1.63	-4.06
0°	3.95	8.95	15.47	-5.7	-11.05	-18.56	0	-3.34	-10.26
-30°	-20.91	-15.72	-10.52	-51.3	-58.95	-70.11	0	-2.45	-9.41
Rear Faces (Locus in Inches)									
	Focus (z)			y			x		
El/Az	0°	30°	60°	0°	30°	60°	0°	30°	60°
30°	8.86	12.09	12.18	50.18	48.60	50.71	0	-7.24	-13.52
0°	3.95	15.35	25.38	-5.7	-18.09	-32.71	0	-9.39	-30.29
-30°	-23.11	-14.59	-5.83	-49.22	-57.96	-74.94	0	-4.46	-21.28

5.6 SURFACE GENERATION ABOUT CENTRALIZED VERTICAL AXIS

This aberration picture leads to the consideration of system configurations in which a meridional screen and mirror profile is rotated about a vertical axis through, or very close to the viewing volume, to generate a 180-degree wrap-around display. Such a system will have no horizontal distortion. Preliminary trials of systems with spherical, and parabolic meridional crosssections indicated that spherical or mildly eccentric elliptical sections must be used to keep the distortion low. In addition, in nearly all configurations, it was found that the requirement that the full vertical field of 60 degrees be visible at all times throughout the complete viewing volume resulted in interference between the line of sight and the physical screen. By re-evaluating the requirements on field of view it seems not too irrational to reduce certain of these requirements. For instance, in any cockpit, when the pilot looks 90 degrees to his right through the copilot's window, it is hardly expected that he will see a 60-degree vertical field. Similarly, a 60-degree field might be seen, looking in the forward direction when the observer's head is located near the front of the viewing volume but probably not when his head is at the rear.

An arbitrary relaxation of these requirements was made after studying photographic scans of cockpit window positions from the pilot's position for aircraft such as the B-52 and KC-135. In each of these aircraft the field of view at the pilot's left side window was about three times that at his right looking through the copilot's right side window, about 50 degrees versus 17 degrees in the B-52 and 45 degrees versus 17 degrees in the KC-135. Similarly, there was evidence that a difference of about 3 feet in viewing distance forward gave a ratio of fields of 25 to 30 degrees versus 15 degrees.

These findings are translated into arbitrary relaxed specifications for the viewing volume. These became 60 degrees for the front of the volume, 40 degrees for the rear (3 feet back), 60 degrees for one side and 30 degrees for the opposite side looking in the same direction from 5 feet away.

It was decided, with these relaxed specifications, to do a parametric evaluation of systems made up of spherical and elliptical vertical cross sections with a vertical axis through the center of the viewing volume generating the surface of rotation. For a pure spherical mirror the only parameters that can be varied, under these conditions, are the vertical position of the viewing volume relative to the center of the sphere, and the radius of the sphere. With the elliptical cross sections the variables are the vertical position of the viewing volume relative to a focus, the elliptical eccentricity, and the vertex curvature which determines the relative size of the ellipse.

5.7 ELLIPSOIDS

The first investigations were done with ellipses. In ACCOS V notation a is the semiminor axis and b the semimajor axis of the ellipse. A measure of the eccentricity is the conic constant which is $K = (a^2 - b^2)/b^2$. With this notation an ellipse with its major axis vertical and having a conic constant of K = -0.25 was analyzed. Its vertex radius was 15 feet. The center of the viewing volume was located 6 feet above the vertex, or 4 feet below the lower focus. See Figures 19 and 20. Table 8 gives the rms spot radii for the various viewing directions and faces of the viewing volume.

The table indicates good promise of success because the greatest error throughout 180 degrees azimuth and the relaxed vertical fields, as described previously, is about 1.7 degrees of "swimming" error. Figures 19 and 20, however, show that a large amount of pre-distortion must be produced in the imagery. The assumption that is made is that the conic constant, or eccentricity, is too great for this ellipse, taking a cue from previous paraboloids that were analyzed and which might be considered as highly eccentric ellipses having K = -1. Investigation of an ellipse with K = -0.3 confirmed this fact, that as the ellipses become more eccentric, the requirement on distortion compensation increases.

The ellipsoids that have been studied are defined mathematically as prolate spheroids; that is, the vertical axis of rotational surface generation is the major axis. The surface can also be generated by rotation about a vertical minor axis in which case the surface becomes an oblate spheroid. Two further surfaces were studied, one a prolate spheroid with K = -0.111111 and another, an oblate spheroid, with K = +0.111111. In both cases the shortest vertex radius was 16 feet. For the prolate spheroid the viewing volume was located either 5 feet or 7 feet from the bottom vertex. The 7-foot distance proved to have the better quality imagery and distortion characteristics. The oblate spheroid was also studied for 5-foot and 7-foot vertex distances for the viewing volume. Again the 7-foot distance gave the best results although these results were not as good as those for the prolate spheroid both in image quality and distortion. Table 9 gives details of these analyses.

5.8 SPHERES

The pure sphere may be though of as a step midway between prolate and oblate spheroids. Because the spherical shape is highly desirable from the production standpoint, a parametric study was also made for the sphere. The radius was arbitrarily set at 16 feet. This left the only variable as the vertical distance of the center of the viewing volume below the center of the sphere. In changing the latter distance through steps of 12, 11, 9, and 8 feet it was found that imagery and distortion improved considerably, as it should, since the viewing volume was approaching the center of the sphere where the optimum

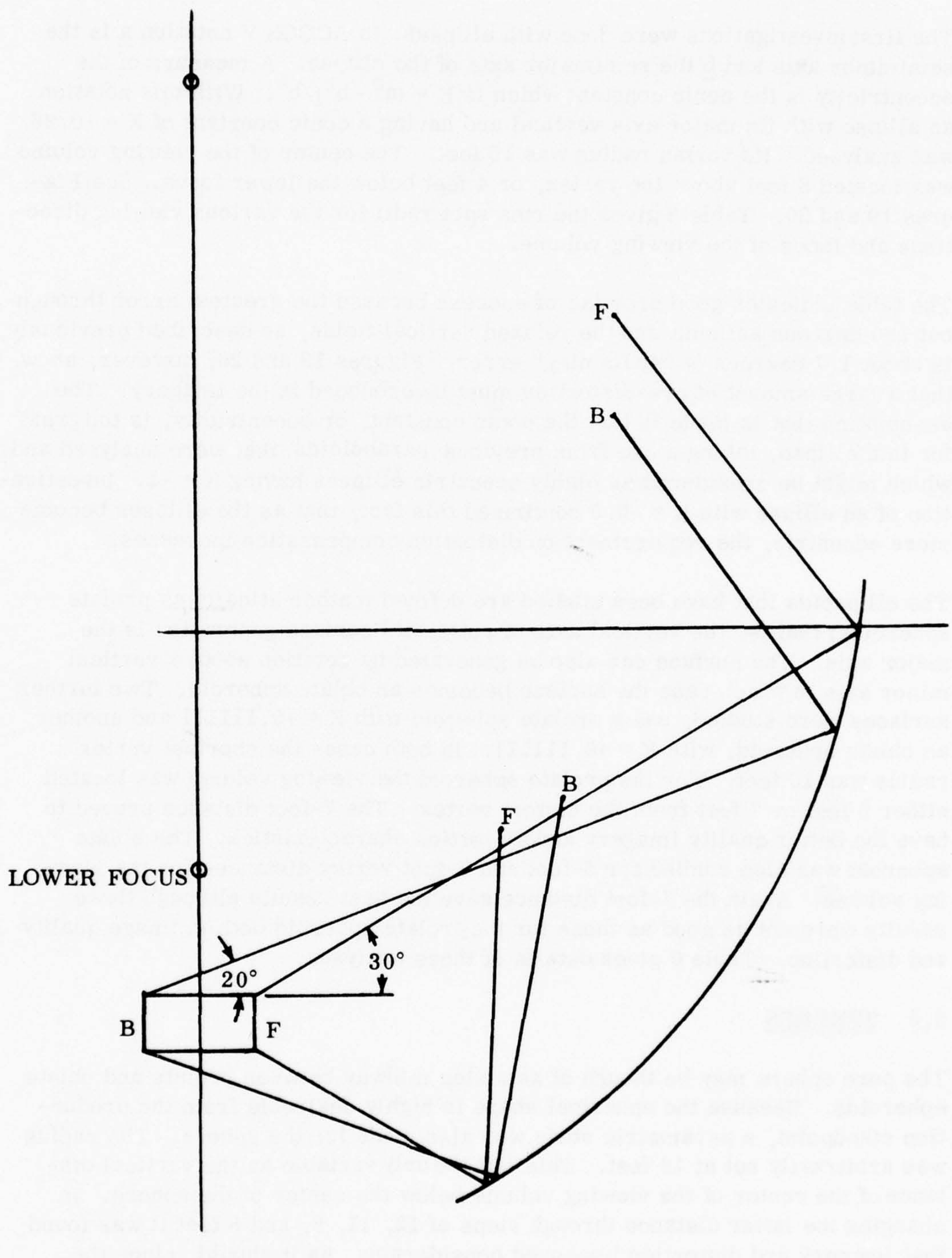


Figure 19. Ellipsoid at 0° Azimuth

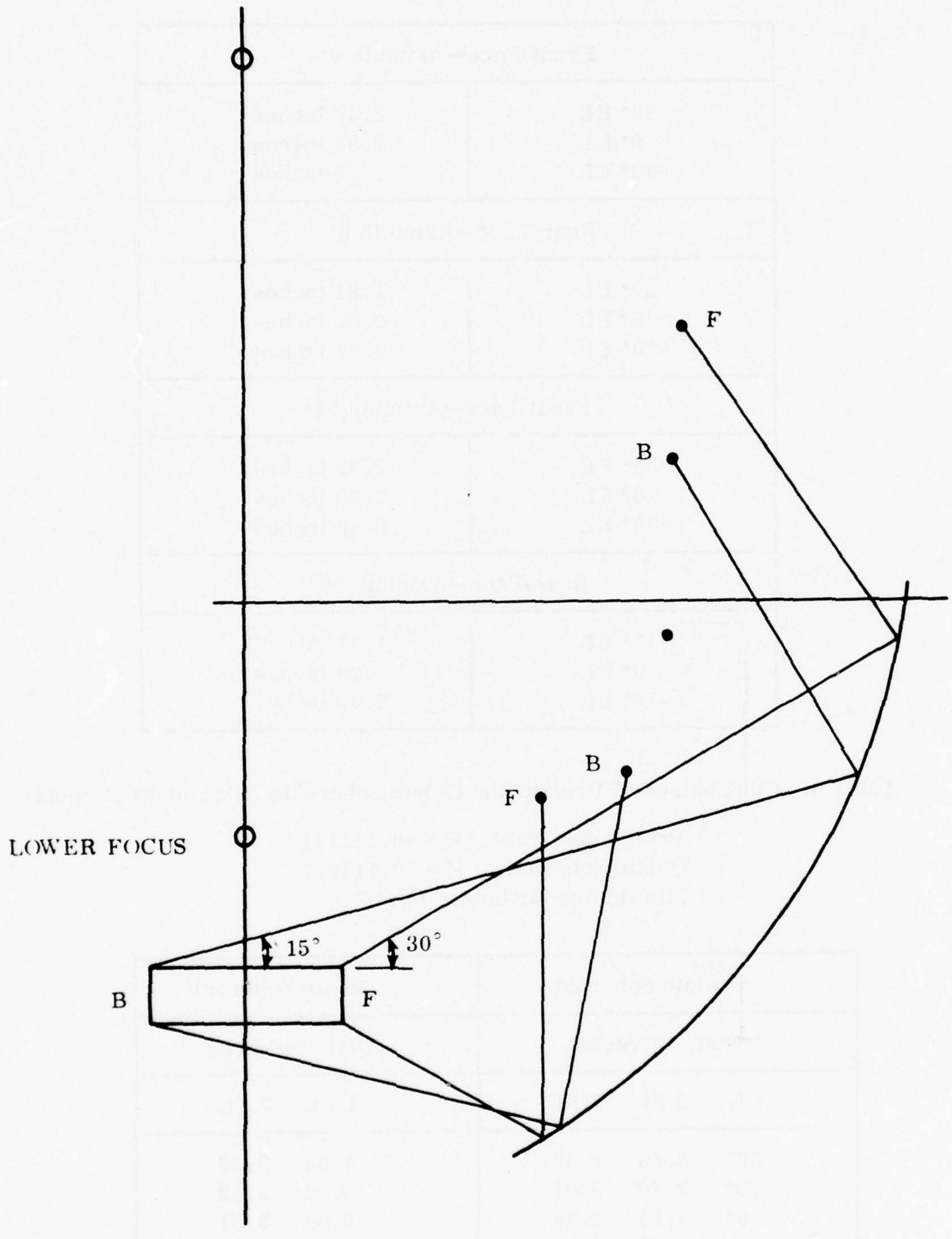


Figure 20. Ellipsoid at 90° Azimuth

Table 8. RMS Spot Sizes for Various Apertures for an Ellipsoid

Front Face—Azimuth 0°	
30° EL	2.47 inches
0° EL	2.62 inches
-30° EL	1.20 inches
Rear Face—Azimuth 0°	
20° EL	1.94 inches
0° EL	2.62 inches
-20° EL	2.57 inches
Front Face—Azimuth 90°	
30° EL	2.39 inches
0° EL	2.20 inches
-30° EL	0.80 inches
Rear Face—Azimuth 90°	
15° EL	1.63 inches
0° EL	2.20 inches
-15° EL	2.49 inches

Table 9. Comparison of Prolate and Oblate Spheroids (RMS Radii of Spots)

Prolate Spheroid: K = -0.111111
Oblate Spheroid: K = 0.111111
Min Radius for both: 16 feet

Prolate Spheroid			Oblate Spheroid	
Dist. to Vertex			Dist. to Vertex	
EL	5 Ft.	7 Ft.	5 Ft.	7 Ft.
30°	3.66	2.52	4.63	3.80
20°	3.20	2.01	4.31	3.32
0°	4.34	2.38	5.63	3.57
-20°	4.15	2.21	5.20	3.13
-30°	2.00	1.10	2.67	1.71

imagery is to be had. However, this distance can only be reduced to the point where interference between the line of sight and the physical screen occurs. Because the imagery looked quite favorable at a distance of 8 feet, the viewing volume was moved forward to eliminate the interference. The volume was moved forward 18 inches so that the vertical diameter of the sphere lay on the rear face of the volume. Table 10 lists the optical data on this configuration. Figure 21 shows the vertical cross section at the 0-azimuth meridian. The points representing best focus for the various conditions seem to cluster near a spherical surface of 7.5-foot radius as shown. The slight deviations from that spherical surface are made up primarily of points for the front surface of the viewing volume looking in the forward direction.

Because of the promising image quality, the relatively low distortion correction needed, and the fact that both screen and mirror surfaces are basically spherical, the configuration was subjected to an optimization routine which was intended to correct some of the defects.

5.9 OPTIMIZATION

The ACCOS V optimization procedure was applied to the optical layout of Figure 21. Variables were the shape of the mirror, shape of the screen, and separation of screen and mirror. The operands, the deviations, were the dX and dY values of the rays that were traced from the chief ray intersections at the screen. An attempt was made to balance the number of variables to the number of operands so as to provide the most favorable program for optimization. However, because of the relative simplicity of the optical system the number of variables is always far less than the number of operands. It must be realized that each dX or dY is one operand and that to make the optimization run meaningful many such quantities must be used to evaluate the system performance for a matrix of eye positions and field angles.

The optimization run that was made showed little change occurring in the variables, indicating that throughout the wide region of optimization exploration the spherical surface, or something very close to it, is the best solution. Because these optimization runs are very expensive and because of the relatively small changes encountered, it was decided to pursue other design concepts.

It had been observed that when using the ACCOS V focus search method that varying results in the rms spot size were obtained depending on the direction of focus searching. For instance, if that search is made in a horizontal direction, the upper part of the field is favored, while the opposite is true for vertical search. The solution is to determine the optimum direction by first tracing a chief ray in the desired direction from a representative point in the viewing volume and then using its calculated direction in the screen region as the focus shift.

Table 10. Spherical System with Viewing Volume Lying Close To Vertical Diametral Axis

RMS Spot Radius Values					
0°—Azimuth					
Elevation	30° 2.90	20° 2.23	0° 2.03	-20° 1.52	-30° 0.71
90°—Azimuth					
Elevation	30° 2.54	15° 1.73	0° 1.70	-15° 1.66	-30° 0.69

Max "Swimming" Error = 2.9/96 = 1.73°

5.10 FINAL DESIGN WORK

The results of a midcontract meeting at AFHRL directed concentration on optimizing the systems for favored observer viewing positions at the lower left and right front corners of the viewing volume rather than using that whole region as an aperture. It was also suggested that emphasis be given to the ellipsoidal layout, Figure 10, and the spherical layout, Figure 21. Both layouts were reexamined using these concepts. The apertures assigned were of 8-inch by 8-inch dimensions with centers at 6 inches by 6 inches by 6 inches from the respective lower left and right front corners of the viewing volume. These apertures were to be rotated to represent off-axis viewing in the ray tracing routines. In the ellipsoidal system it was found that all chief rays in the screen volume were very nearly parallel to the 45-degree axis for the mirror surface, so the focus search was made in that direction. For the spherical system, an examination of the geometry involved indicates that all evaluation can be done in one single azimuth direction because the system is a figure of revolution about a vertical axis through the center of screen and mirror. The 8- by 8-inch apertures, however, must be translated horizontally and longitudinally (toward or away from the mirror) to represent different off-axis viewing directions. In this particular azimuth direction, which is the 0-degree direction halfway between +90 degrees left and -90 degrees right for an observer, the chief rays do have varying vertical slopes. Therefore, the direction of focus search is changed for each elevation angle from +30 degrees upward to -30 degrees downward.

Ray tracing and focus searching with ACCOS V established arrays of prospective screen points for the spherical and ellipsoidal layouts of Figures 21 and 10, respectively. These points are optimum foci for the 8- by 8-inch apertures

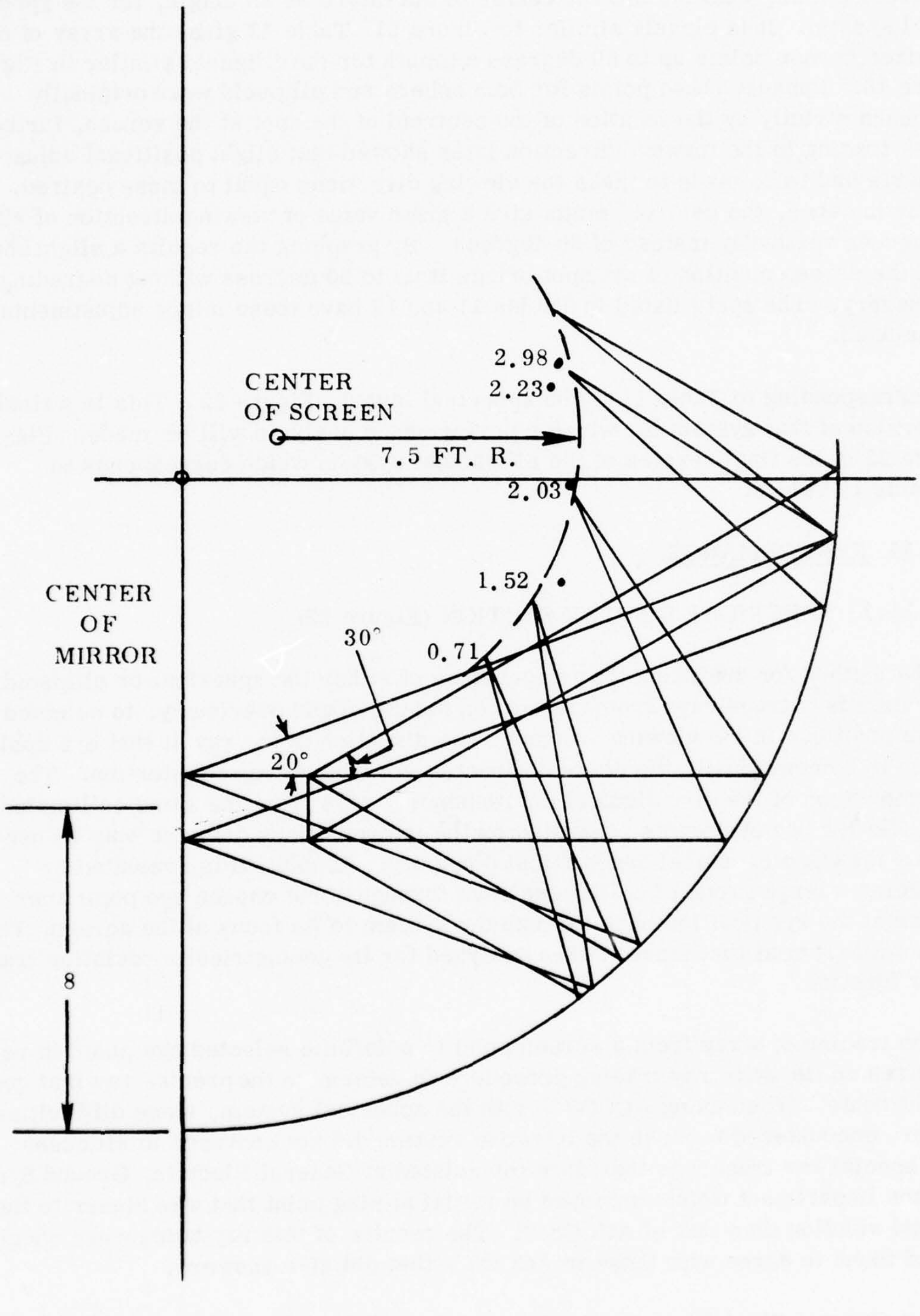


Figure 21. 16-Foot Radius Sphere with Decentered Viewing Volume

for either configuration in the 0-degree azimuth direction. Table 11 shows the screen points, with the mirror center of curvature as an origin, for the spherical system. It is closely similar to Figure 21. Table 12 gives the array of optimized screen points up to 60 degrees azimuth for the ellipsoid similar to Figure 10. Because these points for both sphere and ellipsoid were originally chosen strictly by the location of the centroid of the spot at the screen, further ray tracing in the forward direction later showed that slight positional adjustments had to be made to make the viewing directions equal to those desired. For instance, the centroid might give a mean value of viewing direction of +29.5 degrees vertically instead of 30 degrees. By graphing the results a slight change of the screen position of the spot brings it up to 30 degrees without degrading imagery. The spots listed in Tables 11 and 12 have these minor adjustments included.

Corresponding to Table 11 is the spherical layout, Figure 22. This is a final version of that system for which a performance analysis will be made. Figure 23 is the final version of the ellipsoidal system which corresponds to Table 12 values.

5.11 <u>PERFORMANCE</u>

5.11.1 SPHERICAL DISPLAY SECTION (Figure 22)

The method for analyzing the performance of either the spherical or ellipsoidal system is to trace rays from the screen points, found previously, to selected eye positions in the viewing volume. The direction of the ray at that eye position is compared with the correct direction for evaluation of distortion. The comparison of the directions of corresponding rays from the same collimated bundle for two eye points separated by the interpupillary distance may be used as a measure of lateral and vertical disparity. Resolution is evaluated by tracing a large group of collimated rays through some chosen eye pupil aperture at the eye position back through the system to its focus at the screen. The spot diagram at that focus is then analyzed for its geometrical modulation transfer function.

The tracing of a ray from a screen point to a definite selected eye position requires an iterative ray tracing procedure to determine the precise ray that goes that route. When using ACCOS V with the spherical system, some difficulties were encountered because the iterative routine did not converge in all cases. A special ray trace was therefore formulated at General Electric, Ground Systems Department which employed an initial aiming point that was closer to the final solution than that of ACCOS V. The results of this ray trace were checked and found to agree with those in ACCOS V that did give answers.

The General Electric program was used to evaluate distortion in the spherical system. Figures 24 through 28 show the appearance of a grid for an observer

Table 11. Screen Positions for Image Points for Spherical Mirror System, Figure 22

Desired Elevation	Screen Position*		
	X	Y	Z
30°	0	53	103.8
20°	0	35.5	111.35
10°	0	15.3	115.8
0°	0	-1.4	114.8
-10°	0	-19.3	110.6
-20°	0	-39.12	100.89
-30°	0	-52.64	90.90

*These coordinates are with respect to an origin located at the mirror center of curvature. The Y-axis is vertical, Z-axis horizontal and pointed toward the mirror vertex, and the X-axis completes the right-handed system.

in the aircraft commander position for various locations of his eyes within the 8- by 8-inch aperture. The most obvious deviations are toward the right sides of the grids in the upper and lower corners. The right sides of the grids represent what the aircraft commander would see in looking toward the copilot's side. Figure 29 is a plot of the window outline for a B-52, as seen from the aircraft commander's position, superimposed on the grid of Figures 24 through 28. It shows those parts of the grid which would actually be seen in an aircraft typical of those addressed by this study. It also recalls the discussion in the section on Requirements for a graded field concept.

If that concept is employed, the remaining field shows low distortion for eye positions throughout the 8- by 8-inch aperture. In terms of requirements, Figure 30 gives a composite of all the points that generated Figures 24 through 28 and shows their locations within circles having radi of 3-degree angle (5 percent distortion) centered on the desired coordinates at top and side. There are no violations from +90 degrees to -30 degrees azimuth. From -60 degrees azimuth to -90 degrees azimuth, the points that fall outside the desired distortion limit are primarily those in the upper and lower corners as identified previously in Figures 24 through 28.

Figure 31 is a distortion mapping for the position in the viewing volume for an instructor pilot. It is assumed that he is located at the rear face of the viewing volume and centered between aircraft commander and copilot. The center of his 8- by 8-inch aperture is placed at the same vertical position as the centers of the 8 by 8's for aircraft commander and copilot. Because he is located on

Table 12. Screen Positions for Image Points for Ellipsoidal Mirror System, Figure 23

	Screen Coordinates*								
	AZ = 0°			AZ = 30°			AZ = 60°		
Desired Elevation	X	Y	Z	X	Y	Z	X	Y	Z
30°	0	116.18	-38.58	53.76	106.5	-46.5	97.23	85.50	-84.37
20°	0	103.42	-18.05	55.23	92.5	-22.8	101.87	71.72	-61.60
10°	0	88.62	-1.91	55.02	78.38	-5.97	102.94	56.36	-35.43
0°	0	72.74	10.30	53.41	62.00	9.00	100.01	39.92	-9.75
-10°	0	56.46	19.16	50.62	46.00	18.5	93.91	23.72	8.45
-20°	0	40.15	25.22	46.97	30.5	26.0	85.94	8.55	18.58
-30°	0	23.97	28.93	42.61	16.0	28.9	76.77	-5.54	23.19

*The origin for these coordinates is located 120 inches from the ellipsoid vertex along its axis of rotational generation at 45 degrees to horizontal. The Y-axis points upward, the positive Z-axis along the 45-degree axis of generation and pointing toward the ellipsoid vertex, and the X-axis horizontal and completing the right-hand coordinate system.

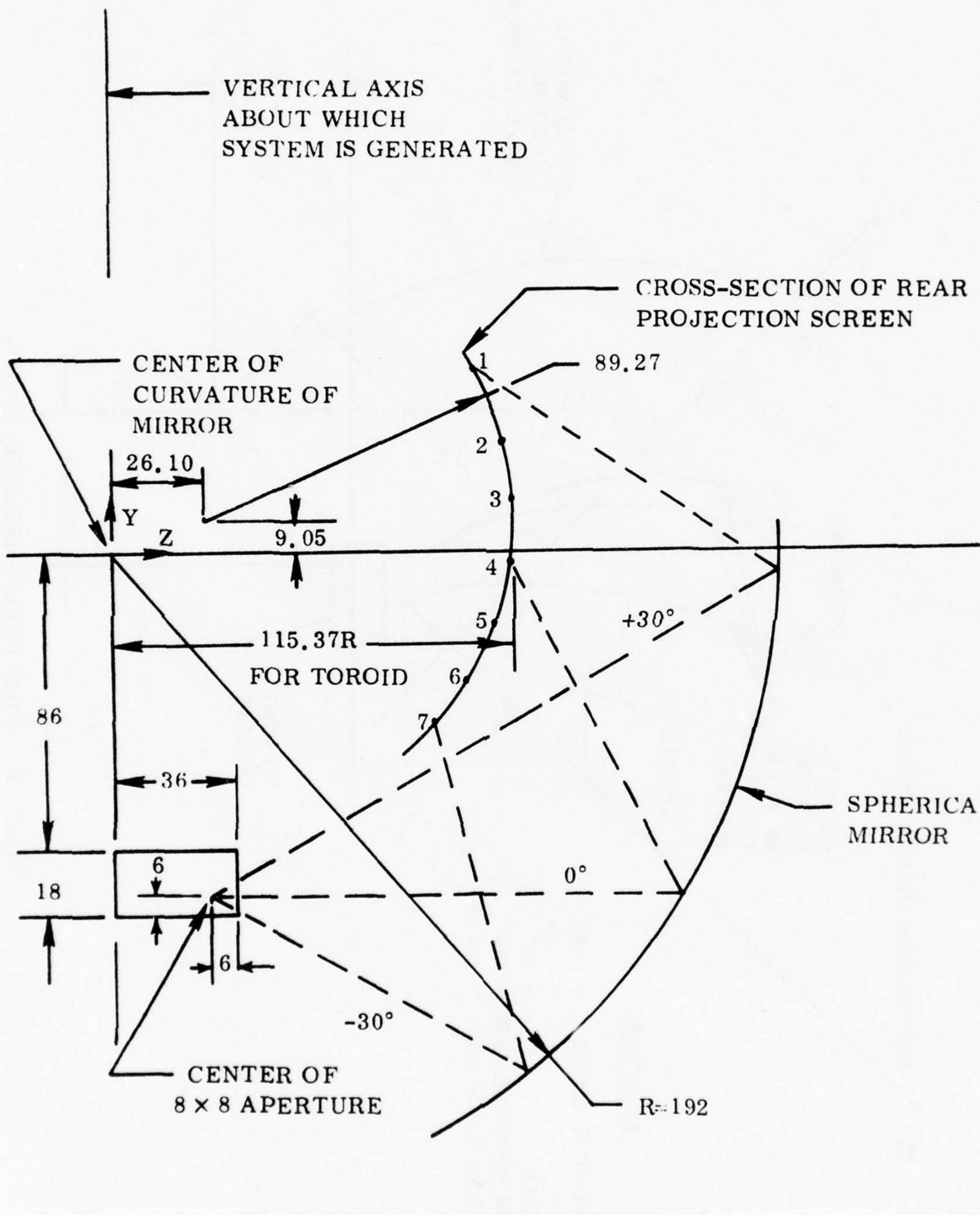


Figure 22. Final Spherical Display Section

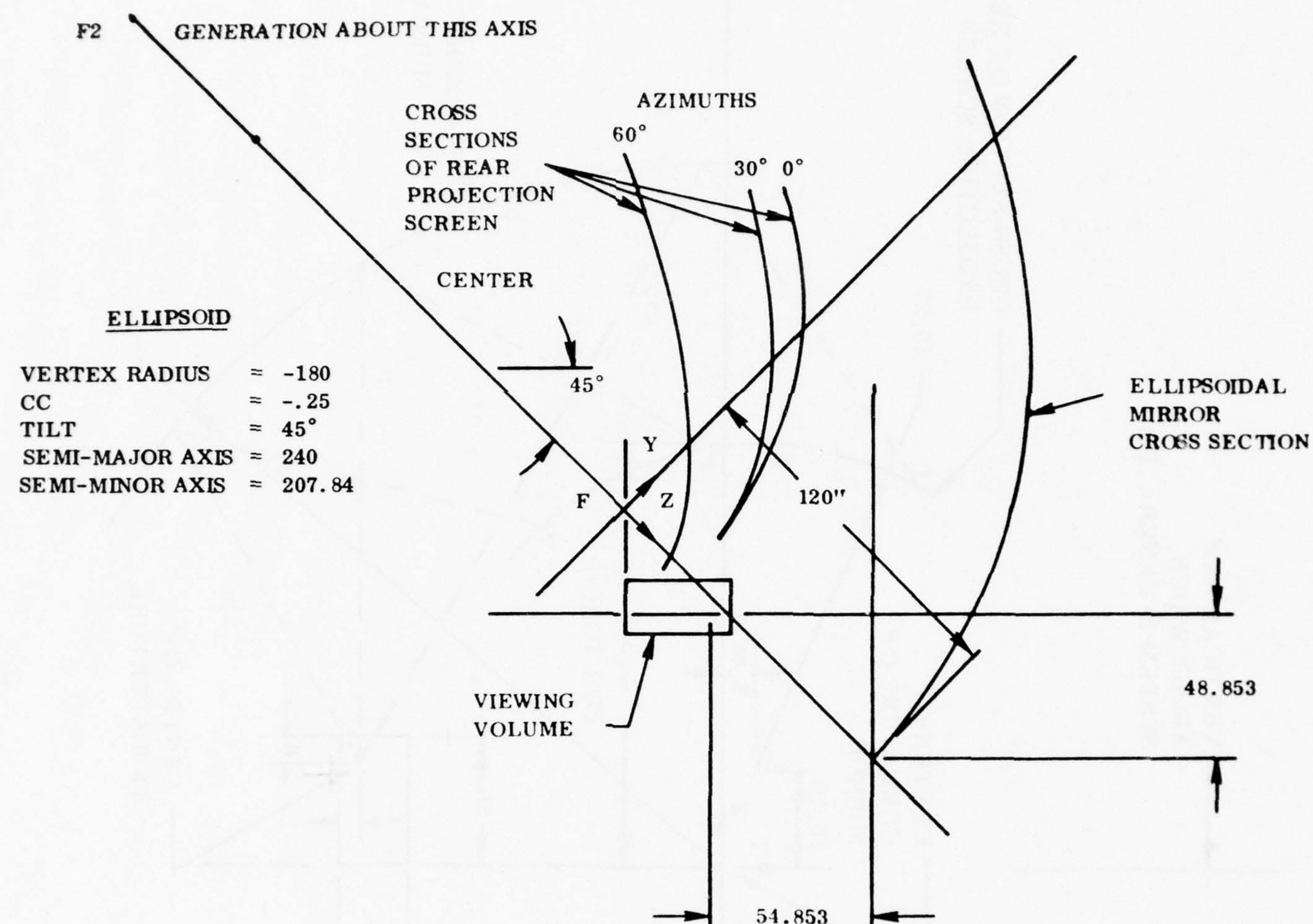
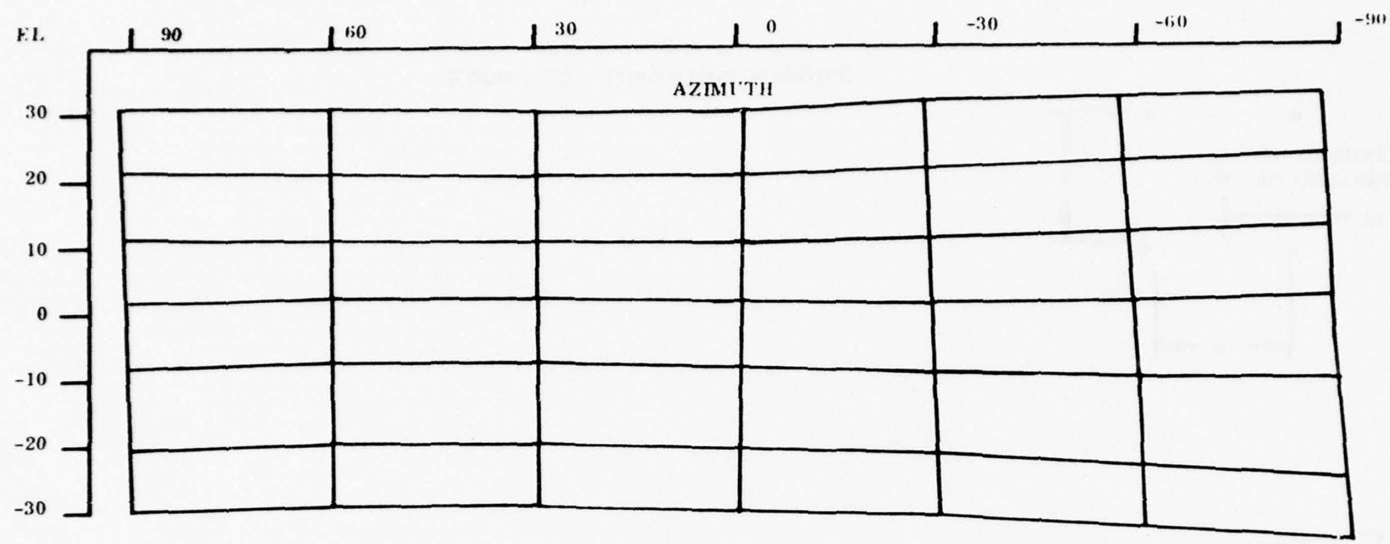


Figure 23. Final Ellipsoidal Display Section



FIELD APPEARANCE FROM "*" EYE POSITION WITHIN 8" BY 8" HEAD VOLUME ON PILOT SIDE OF AIRCRAFT. APPEARANCE FOR COPILOT IS MIRROR IMAGE OF THE DIAGRAM ABOVE THROUGH AZIMUTH = 0 LINE AND DIAGRAM AT RIGHT ABOUT CENTERLINE OF AIRCRAFT.

FIGURES 25 THROUGH 28 ARE SIMILAR TO FIGURE 24 EXCEPT FOR "*" POSITION.

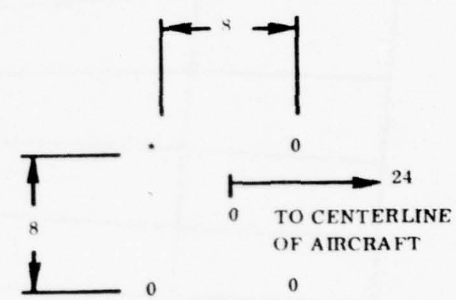


Figure 24. Distortion Mapping. Field Appearance for Selected Monocular Eye Position

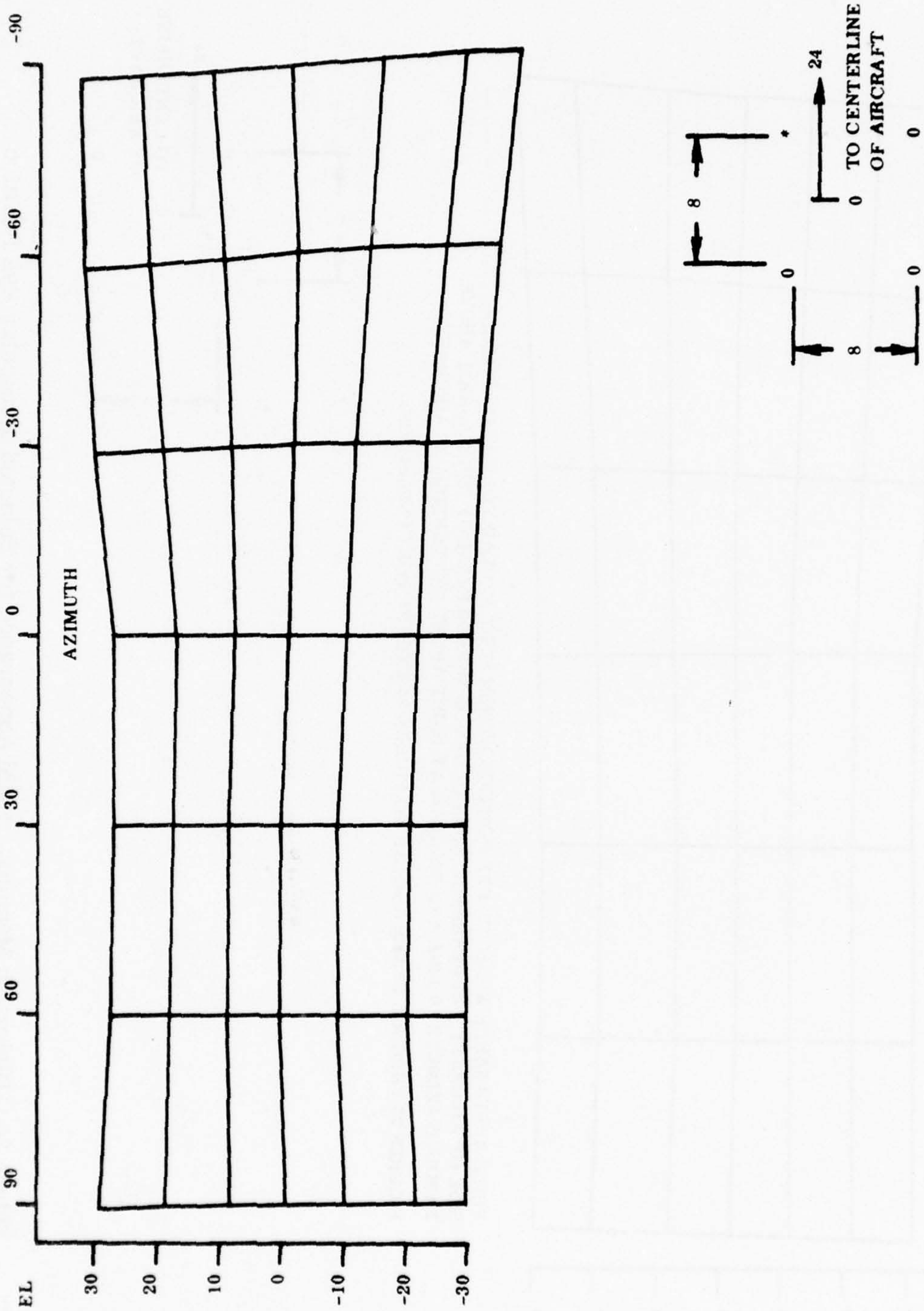


Figure 25. Distortion Mapping

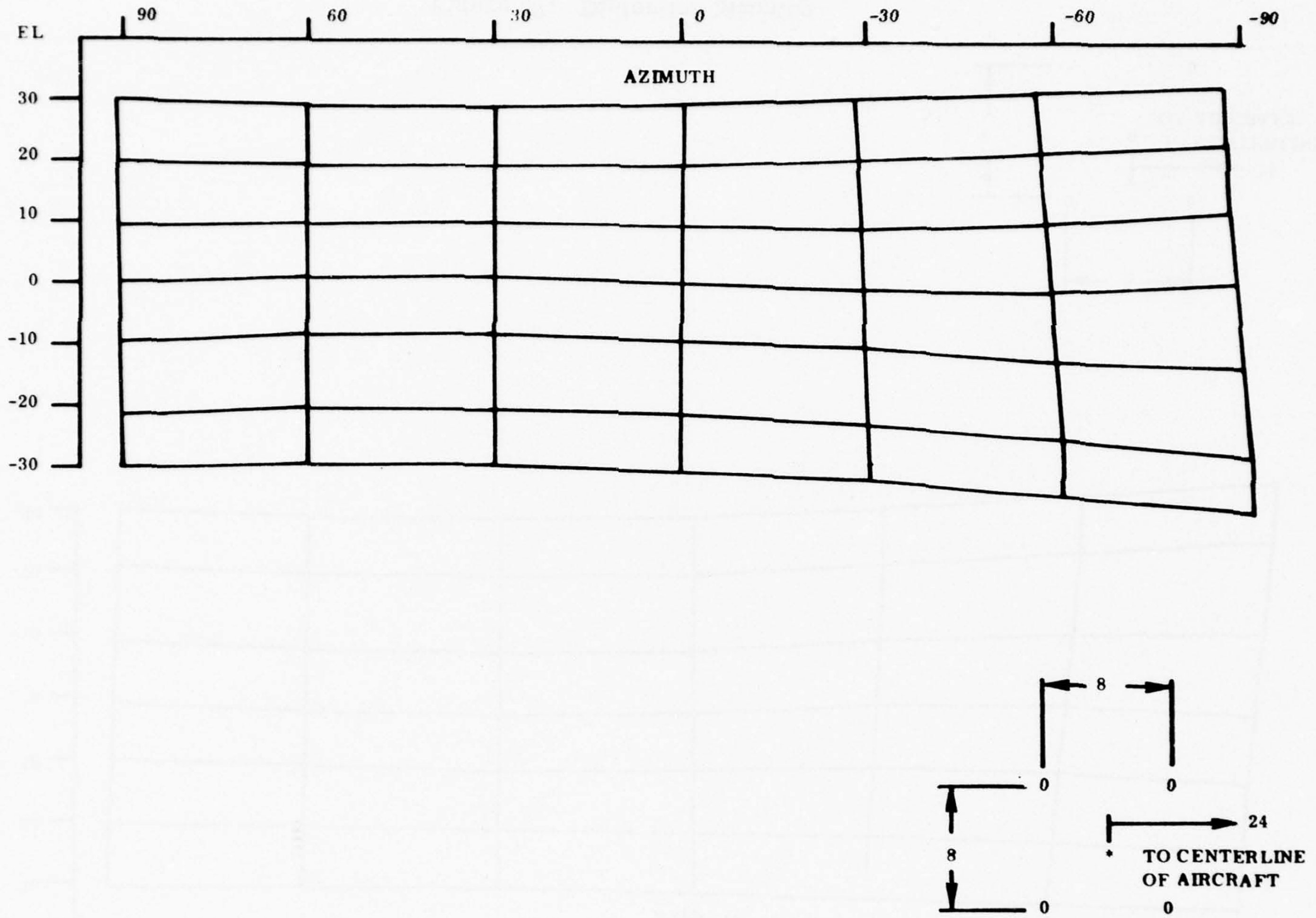


Figure 26. Distortion Mapping

Figure 27. Distortion Mapping

Figure 28. Distortion Mapping

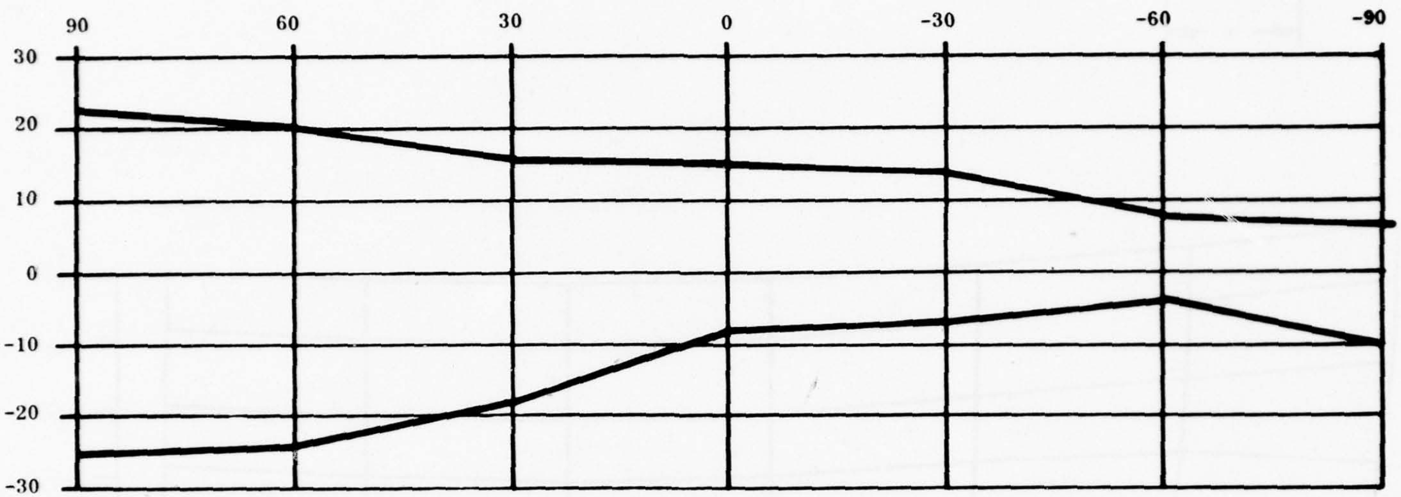
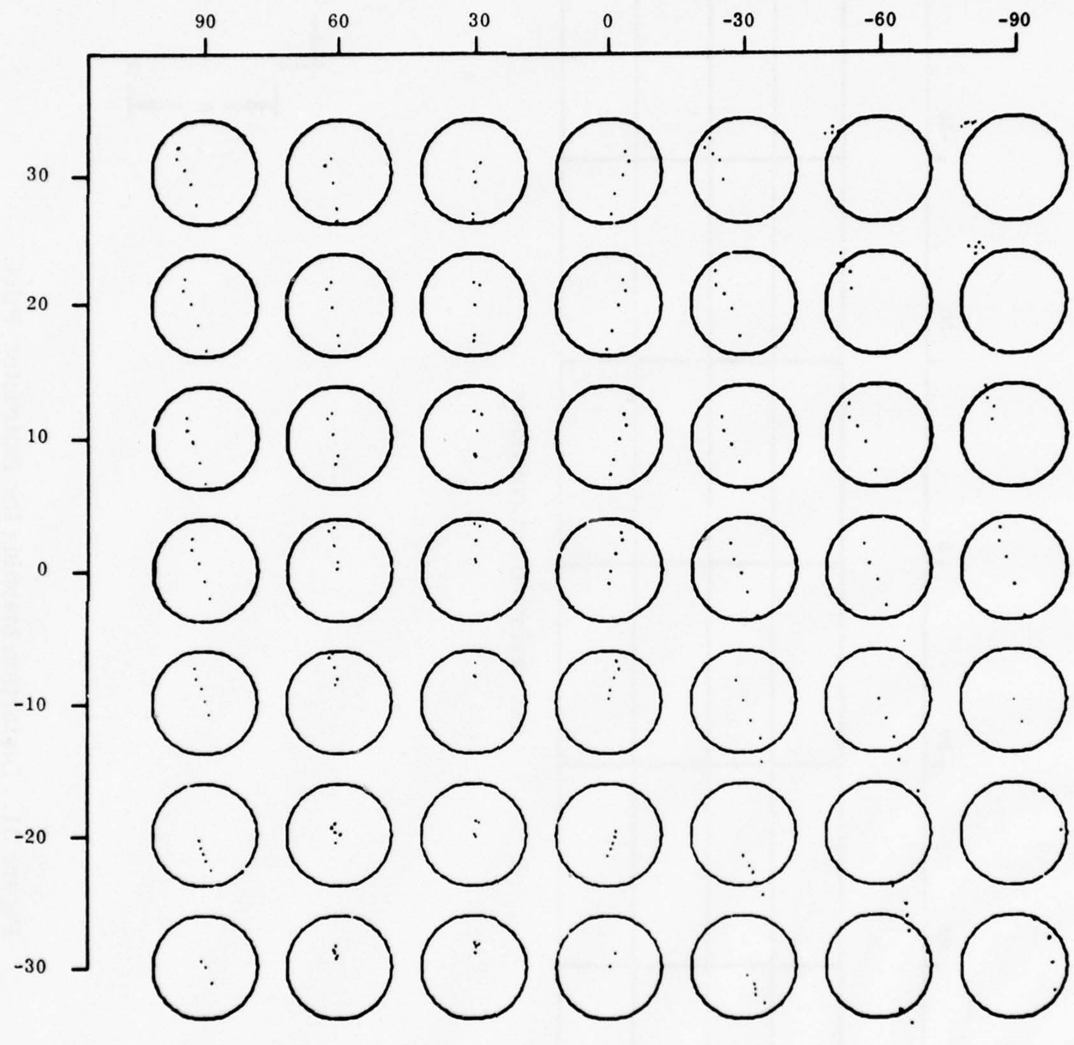


Figure 29. B-52 Window Outline



COMPOSITE OF ALL FIVE VIEWING POSITIONS OF FIGURES 5-16 THROUGH 5-20 SHOWING THEIR VARIATION IN POSITION AGAINST A CIRCLE OF 3-DEGREE RADIUS REPRESENTING 5 PERCENT (OF VERTICAL FIELD) DISTORTION TOLERANCE.

Figure 30. Composite Spot Diagram

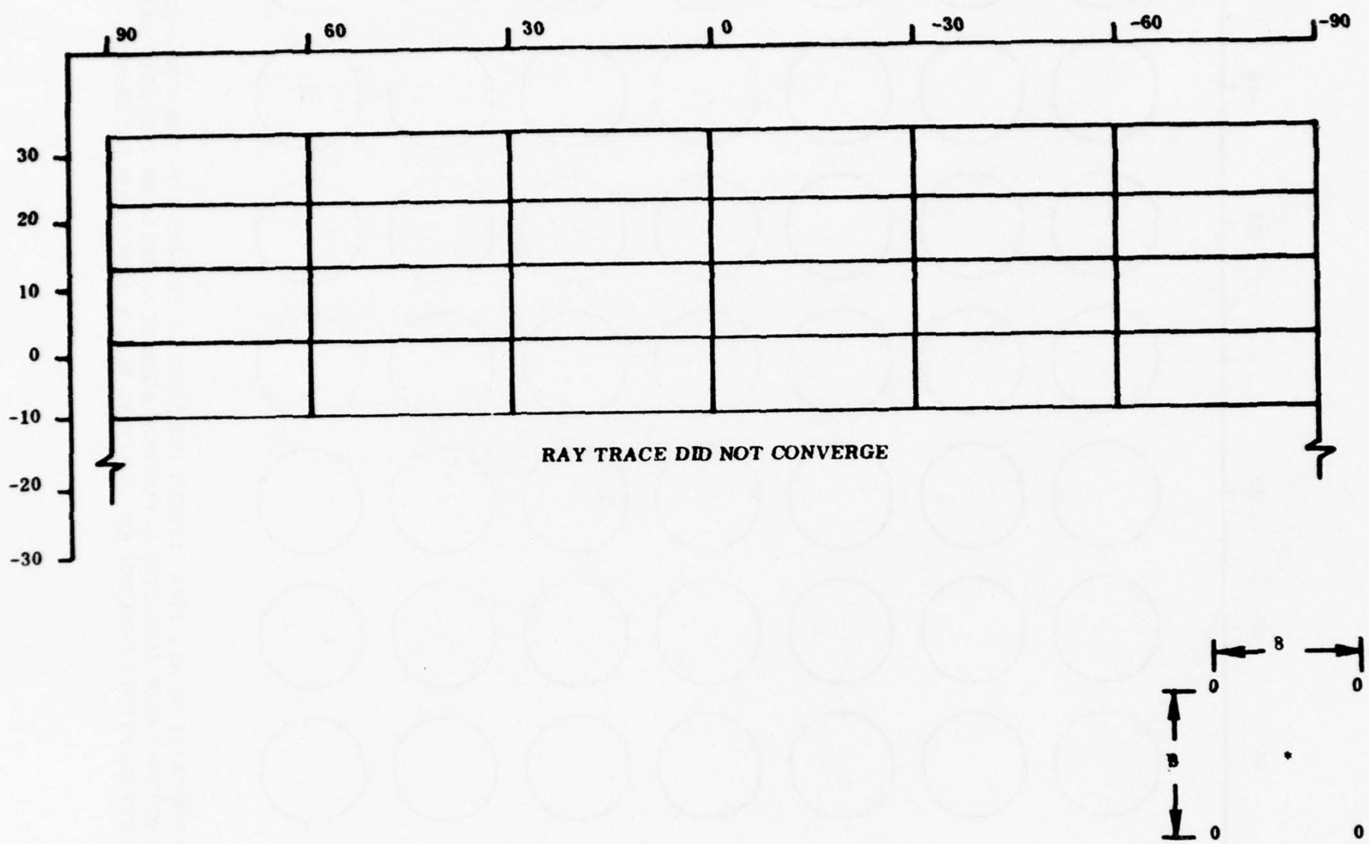


Figure 31. Distortion Mapping for Instructor-Pilot

the vertical axis that generates the optical system, all imagery has the same azimuth characteristics throughout the 180 degrees. Within the region that ray tracing results were obtained, the main characteristic seemed to be increased elevation readings. At 30 degrees it calculated to 32.89 degrees; at 20 degrees, 22.7 degrees; at 10 degrees, 13.29 degrees; at 0 degrees, 2.10 degrees; and at -10 degrees, -8.9 degrees. This characteristic was present throughout the 8- by 8-inch aperture which means that swimming distortion is low. The only effect in going to this location from either of the other two is a gradual upward positioning of the field.

It is difficult to quantify the extent of swimming distortion. The effect is caused by the differences in relative directions to various portions of the field of view as the eye moves throughout the viewing volume. The viewed objects, in effect, take on different localized magnifications in various directions during the observer's head movement. If any of this effect is present in this display, it will be seen mainly in the cross-cockpit direction and in the upper parts of the field. This was observed when superimposing transparencies of Figures 24 through 28. A laboratory demonstrator, however, was set up during the midcontract meeting at Daytona and essentially none of this effect was observed. The demonstrator employed three juxtaposed mirrors from another project and a temporarily erected rear-projection screen which closely approximated, in minature, the spacings of the display system elements of Figure 22. The field of view was approximately 108 degrees by 30 degrees. The laboratory setup also demonstrated good imagery throughout the field. The main error in the display was a slight mispositioning of one of the three mirrors, giving a disjointed appearance to lines in the scene crossing over the joint between the mirrors.

There is evidence of astigmatism in the imagery as can be seen by the linear array of points in the vertical direction in Figure 30. This is due to the wide separation—48 inches—of the two 8- by 8-inch apertures (aircraft commander and copilot positions) versus the height of the 8- by 8-inch aperture of only 8 inches, all related to the far-off axis geometry. The position of the screen points was found by the minimum rms radius focus which is very close to the focus for the relatively wide horizontal fan of rays rather than the focus of the narrow vertical fan. It will be shown later that resolution is unaffected by this result.

The eye separation was changed from 8 inches to the interpupillary distance, 2.5 inches. Three vertical levels within the 8- by 8-inch aperture were filled with these pairs, making nine total pairs per viewing direction to evaluate lateral convergence. The results of the computer analysis are shown in Table 13. For every azimuth and elevation angle nine values of convergence (in diopters) are listed corresponding in tabular position to the positions of the pairs within the 8- by8-inch aperture looking toward the mirror. The diopter values are negative if the rays diverge from a point in front of the observer.

Table 13. Convergence Values (Diopters) for the Spherical Display System

ELEVATION	AZIMUTH 90			60			30			0			-30			-60			-90		
	-.017	-.012	-.006	-.023	-.021	-.018	-.022	-.024	-.045	-.011	-.015	-.019	-.019	-.014	-.008	-.033	-.029	-.026	-.047	-.045	-.044
30	-.007	0	.007	-.014	-.011	-.007	.043	-.043	0	.003	-.003	-.009	-.010	-.003	.004	-.028	-.024	-.020	-.045	-.043	-.042
	0	.019	.031	0	.004	.009	.001	-.001	-.003	.024	.015	.007	.003	.013	.024	-.022	-.018	-.012	-.043	-.041	-.039
	-.011	-.006	.001	-.022	-.020	-.017	-.022	-.023	-.024	-.007	-.011	-.016	-.009	-.003	.005	-.023	-.018	-.012	-.041	-.039	-.037
20	.002	.009	.017	-.012	-.009	-.006	-.012	-.014	-.015	.007	.001	-.004	.004	.013	.023	-.014	-.008	-.001	-.038	-.035	-.032
	.022	.032	.045	.001	.005	.009	.001	-.001	-.002	.028	.020	.012	.026	.039	.056	-.002	.006	.017	-.033	-.030	-.027
	-.008	-.003	.003	-.023	-.021	-.019	-.024	-.025	-.026	-.007	-.012	-.015	-.001	.006	.014	-.008	-.001	.006	-.031	-.027	-.024
10	.004	.010	.018	-.015	-.012	-.009	-.016	-.017	-.018	.005	0	-.005	.014	.023	.034	.006	.015	.026	-.024	-.020	-.015
	.021	.029	.039	-.004	-.001	.003	-.005	-.007	-.007	.021	.014	.009	.036	.049	.064	.029	.044	.063	-.013	-.008	-.001
	-.003	.002	.008	-.021	-.019	-.017	-.023	-.024	-.024	-.004	-.008	-.012	.010	.017	.025	.017	.026	.036	-.005	0	.007
0	.008	.013	.020	-.013	-.012	-.009	-.015	-.016	-.017	.006	.001	-.003	.024	.032	.042	.037	.049	.064	.010	.019	.029
	.021	.027	.034	-.005	-.002	0	-.007	-.008	-.009	.017	.012	.007	.041	.051	.063	.068	.086	.108	.038	.053	.073
	.001	.005	.010	-.019	-.018	-.016	-.021	-.022	-.022	-.003	-.006	-.009	.016	.089	0	.035	.045	.055	0	.085	.046
-10	.009	.014	.019	-.013	-.011	-.009	-.015	-.016	-.017	.005	.001	-.002	0	0	.098	.053	.064	.077	.050	.062	.076
	0	0	.078	-.006	-.004	-.002	-.009	-.010	-.010	0	0	.035	.039	.046	.055	.075	.087	.102	.084	.101	.121
	.005	.009	.013	-.015	-.014	-.012	-.017	-.018	-.018	.001	-.002	-.005	.021	.026	.032	.046	.054	.062	.054	.062	.071
-20	.011	.015	.019	-.011	-.009	-.007	-.013	-.014	-.014	.006	.003	0	.028	.034	.040	.057	.065	.074	.069	.078	.088
	.017	.021	.025	-.006	-.004	-.002	-.008	-.009	-.010	.012	.008	.005	.036	.041	.048	.069	.077	.087	.086	.095	.106
	.007	.011	.027	-.012	-.011	-.009	-.014	-.015	-.015	.003	0	-.002	.071	.027	.032	.047	.054	.061	.057	.064	.071
-30	0	0	0	-.009	-.007	-.006	-.011	-.012	-.012	0	0	0	.027	.032	.037	.054	.061	.068	.067	.074	.081
	0	.069	.023	-.005	-.004	-.002	-.008	-.008	-.009	0	0	0	.033	.037	.043	.062	.068	.075	.077	.084	.091

The 4-milliradians convergence listed in the requirements for the study becomes -0.063 diopter. Positive azimuth is toward the left from the straightforward, or 0° direction.

To be acceptable, $-0.063 < \text{convergence} < 0$. Because of the extreme field angles and very large aperture required in this display system study, it was found quite difficult to attain collimation over the large region of concern let alone keeping all of that correction at, or on one side only, of infinity. The results of the ray trace for the paired eye points gave a distribution of about 50-50 on plus and minus convergence. Much of the plus convergence was in the region outside the useful field, as depicted in Figure 29. The largest value was +0.121 diopters which occurred for the viewing direction (-90 degrees azimuth, -10 degrees elevation) for the lower right corner of the 8- by 8-inch aperture. This corresponds to the aircraft commander moving his head down to the lower right corner of his 8- by 8-inch viewing area and looking through the copilot's right side window. This is not a very typical viewing situation.

As a criterion for the remainder of the convergence values, appeal is made to Table 14 which is a reprint from a technical article.[2] In that table the most acceptable tolerance found for collimation for the unaided eyes is 17 arc minutes for divergence, convergence, and dipvergence as stated in the MIL-HDBK-141 Optical Design (1962).[3] Seventeen minutes of arc is 0.0049 radian in comparison with 0.004 radian for the study requirements. The "relaxed" convergence requirements would allow a tolerance of ±0.077 diopter. Using this criterion there were 21 violations out of 441 cases. Even then a large percentage of the 21 violations were in portions of the field which, under normal circumstances, are not used.

Resolution was evaluated by tracing backward a group of 100 rays through an assumed eye pupil of 4mm diameter. The spot diagram formed by this bundle at the screen was analyzed by ACCOS V for the geometrical modulation transfer function (MTF).

The 6 arc-minute resolution study requirement for the center of the field is equivalent to a spatial frequency of 0.235 cycle/mm at the screen location taking into account the 96-inch focal length of the mirror. The MTF was computed for several different viewing directions with the eye arbitrarily located at the center of the 8- by 8-inch aperture. Table 15 lists the results. The Display section obviously does not detract very much from the image quality. The system is primarily television projector limited. A television system with 627 realizable lines will produce a line spacing on the screen of this spherical system of 6 arc-minute separation. A 1000-line raster television system will produce lines with a separation of 3.76 arc minutes. The spherical display section is a figure of rotational symmetry about a vertical axis through the center of curvature of the mirror. There is consequently no difference in imagery for

Table 14. Visual Tolerances

Eye/Instrument	Tolerances								References
	Magn. diff.	Lum. diff.	Color diff.	Field curv.	Astigm. diff.	Collimation			
						Converg.	Diverg.	Dipverge.	
Binoculars Type I (7 by 50)	1%			2 D.		14 min.	28 min.	14 min.	MIL-B-17311 (SHIPS) 25 September 1952
Type II (6 by 42)	1%			1 D.					
Binoculars M19 & M20 (7 by 50)	2%					0	40 min.	15 min.	MIL-B-60884A (MU) 12 March 1970
Binocular (7 by 50)						0	24 min.	15 min.	Shenker, M. (1972)
Binocular collimated projection (tol. for eyes)						9 min.	* 3 min. 22.5 sec.	3 min. 22.5 sec.	Gold, T. (1972)
Eyes	1-2%	10%	12%			17 min.	17 min.	17 min.	MIL-HDBK-141 Optical Design (1962)
Eyes					0.75D.				Borish, I.M. (1970)
Eyepieces				1 D.	1 D.				Shenker, M. (1972)
Spectacles						9 min.	9 min.	4 min.	Sheppard, C.F. (1952)
"Duoview" binocular system (tol. for eyes)						<20 min.	<10 min.	<10 min.	Spooner, A.M. (1973)

*3'22.5" = 1 milliradian

Table 15. Geometrical MTF Values for Spherical Display Section

Viewing Direction		MTF			
		Target Lines Vertical		Target Lines Horizontal	
Azimuth	Elevation	0.25 cycles/MM	0.50 cycles/MM	0.25 cycles/MM	0.50 cycles/MM
0°	0°	0.960	0.846		
0	30	0.963	0.858	0.974	0.897
0	-30	0.993	0.973	0.993	0.972
-60	0	0.950	0.808		
60	30	0.963	0.857	0.975	0.901
60	-30	0.995	0.981	0.995	0.980
-60	30	0.981	0.927	0.982	0.929
-60	-30	0.973	0.896		

any vertical cross sections throughout the 180-degree field. The fall-off in image quality in any areas of the display will be due to the individual performances of the separate television projectors in their off-axis field positions.

5.11.2 ELLIPSOIDAL DISPLAY SECTION (Figure 23)

The ellipsoidal display system of Figure 23 was analyzed throughout the total vertical field of 60 degrees and in azimuth from +60 degrees to -60 degrees. The complete 180-degree field in azimuth was not evaluated because the field up to ±60 degrees was showing results with some undesirable characteristics. Figure 23 shows that the projection of the field points for 30 degrees and 60 degrees azimuth into the plane of the diagram shows interference between upward viewing directions and the screen. In the 60-degree azimuth direction a requirement to maintain the full 30-degree (upward) field would mean loss of the lower field below -10 degrees. Or if the lower field is of greater importance the attainment of -30 degrees (downward) elevation at 60 degrees azimuth would mean the loss of the whole upper field from about 0 degrees upward.

The other undesirable aspect for the ellipsoidal system is the shape requirement for the large mirror. As distinguished from a spherical system in which the large mirror can be made up of identical segments, the large ellipsoidal mirror must be made up of a large group of individual one-of-a-kind segments, or, at best, paired segments from either side of a plane of symmetry.

The *logic of using an ellipsoidal mirror* is that of placing the viewing volume close to one of the foci of the ellipsoid. This is illustrated in Figure 23. The bundles of rays representing various field directions pass much closer to the focus than in the spherical system, resulting in reduced spherical aberration and distortion. However, to overcome the screen interference discussed above, the viewing volume must be moved away from the focus. This was learned in the spherical system and a relatively radical movement of the viewing volume was made to a position on the vertical axis of surface generation. An unforeseen spinoff of this modification was the attainment of nearly equal imagery throughout the 180-degree horizontal field.

A distortion mapping, similar to that for the spherical system, was made for the ellipsoidal system. These mappings are illustrated in Figures 32 through 36. The same interpretation is to be made as for those seen previously for the spherical system.

The ellipsoid seems to have a better mapping response than the sphere, particularly in azimuth error. Although the outer portions of the map, at ±90 degrees azimuth, are not present, the general tendencies are evident. The distortion is very well corrected on the aircraft commander's (or copilot's) side of the display but gradually becomes worse when looking cross-cockpit. The ellipsoidal

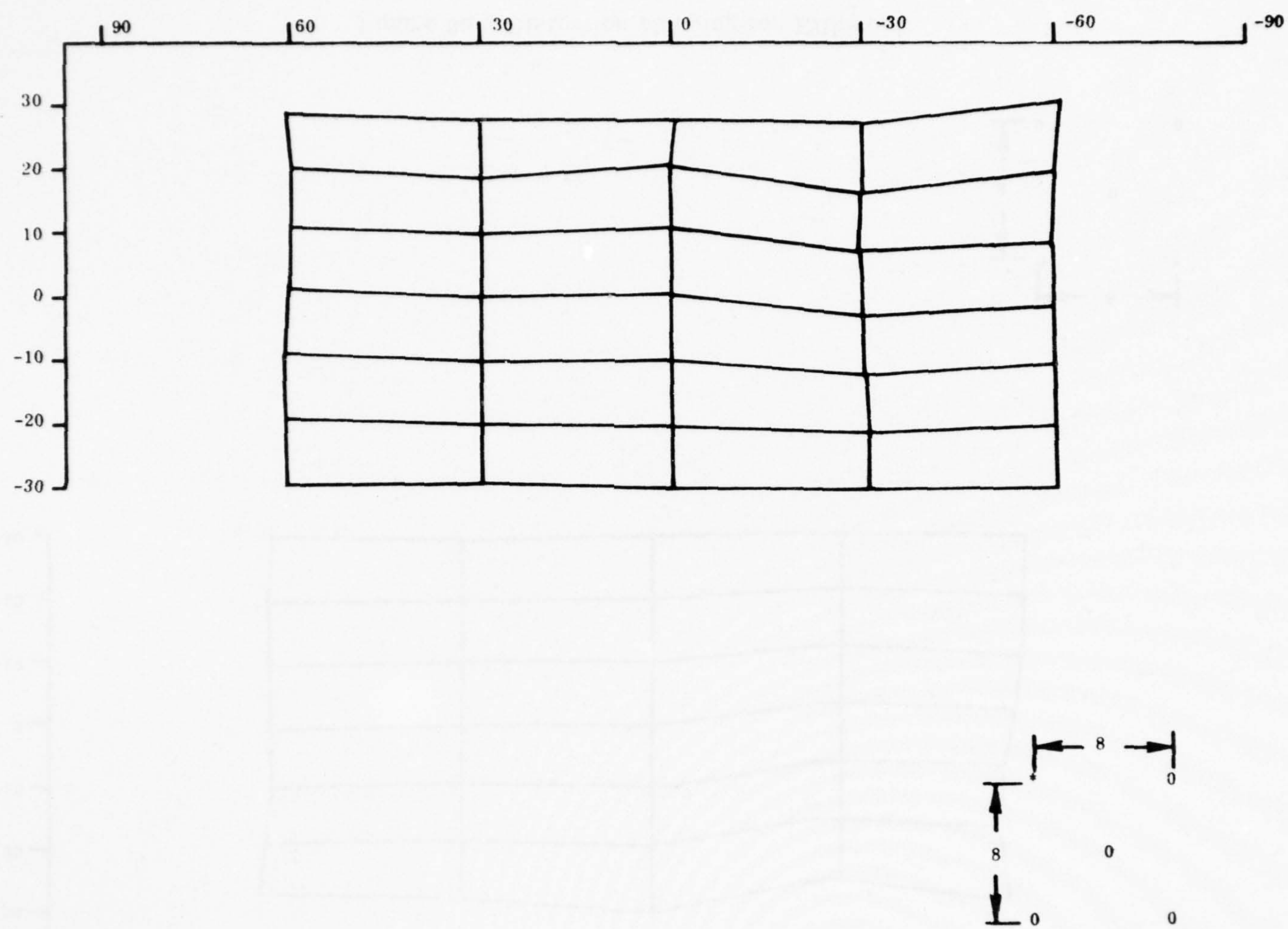


Figure 32. Distortion Mapping for Ellipsoid

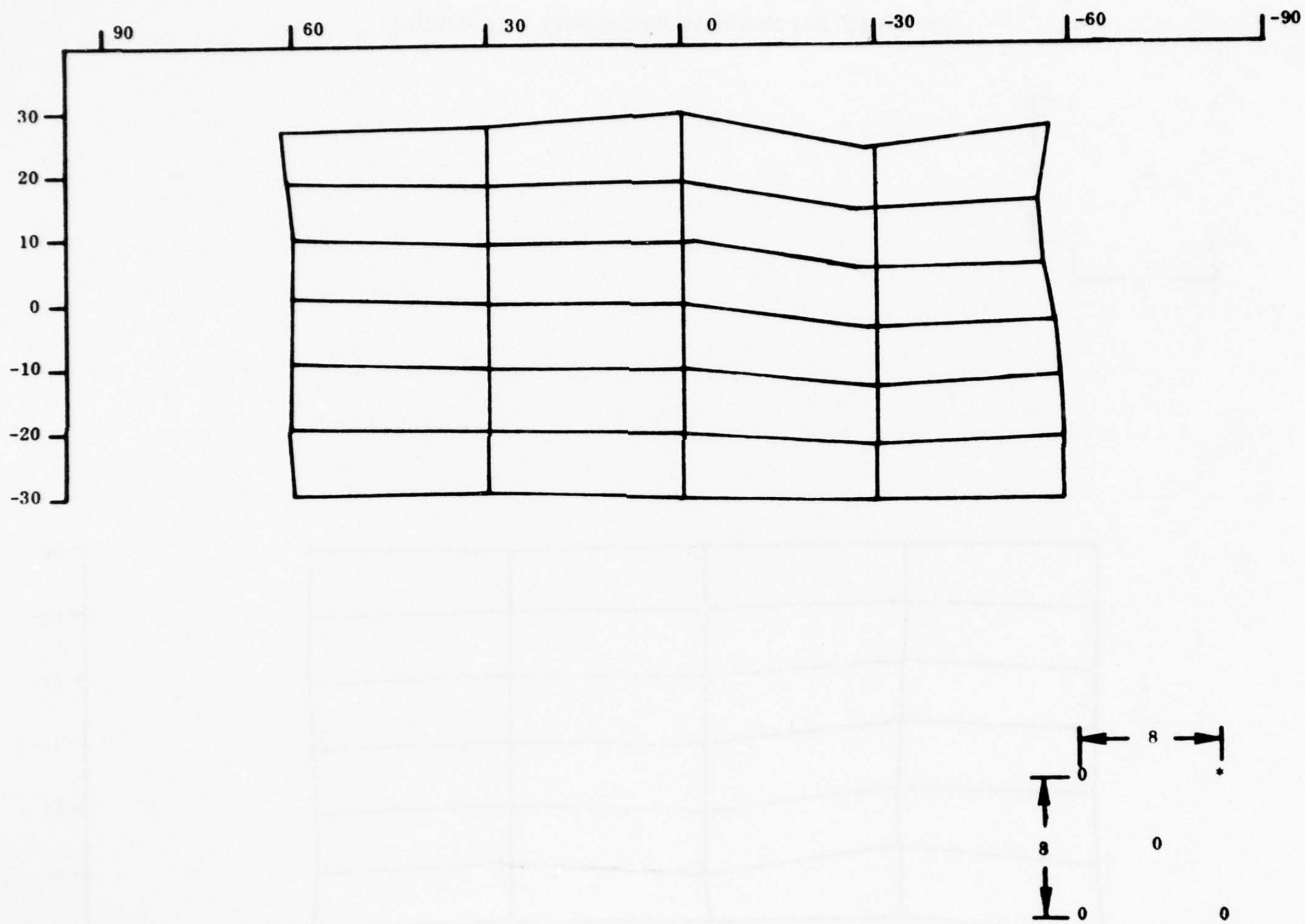


Figure 33. Distortion Mapping for Ellipsoid

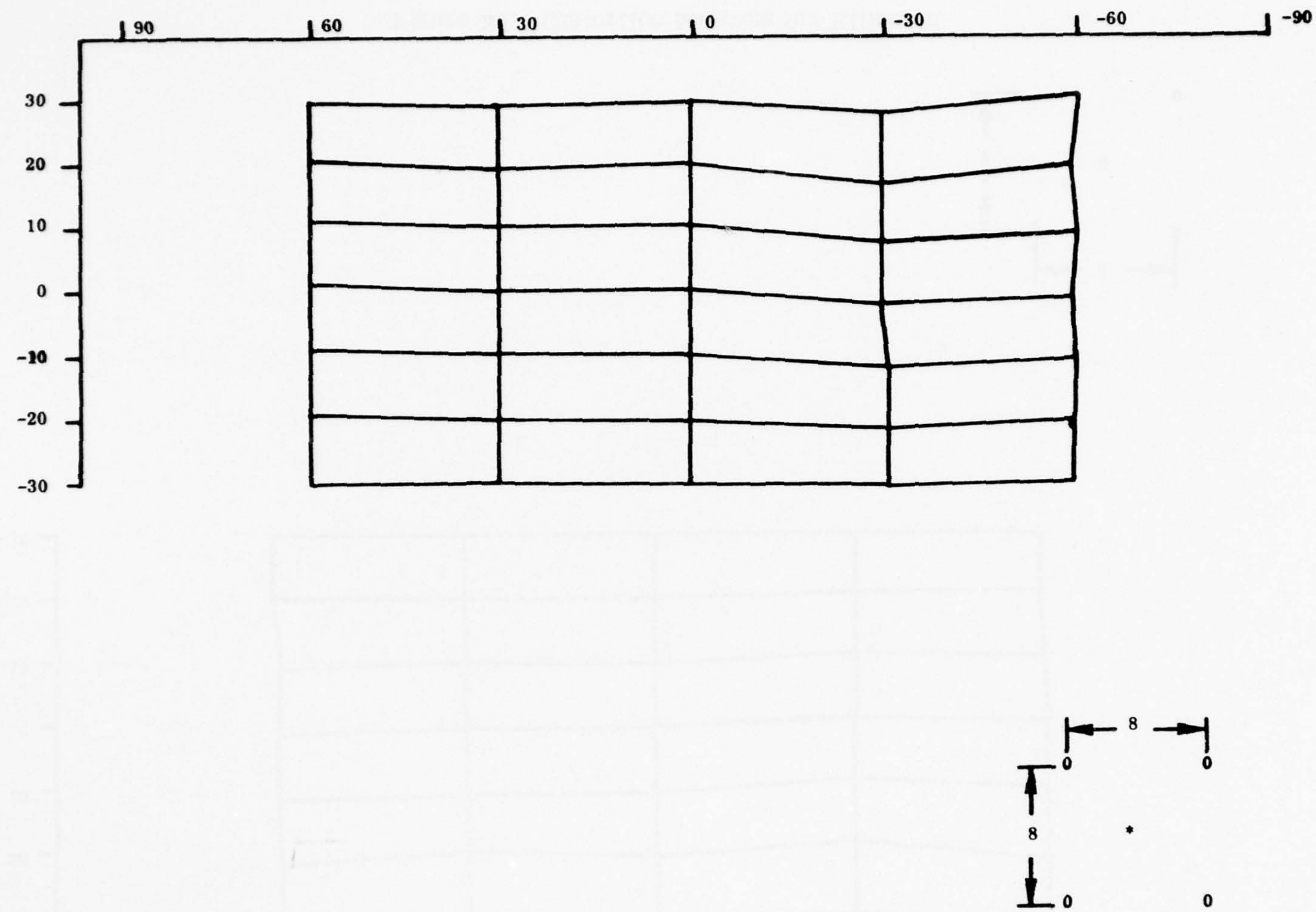


Figure 34. Distortion Mapping for Ellipsoid

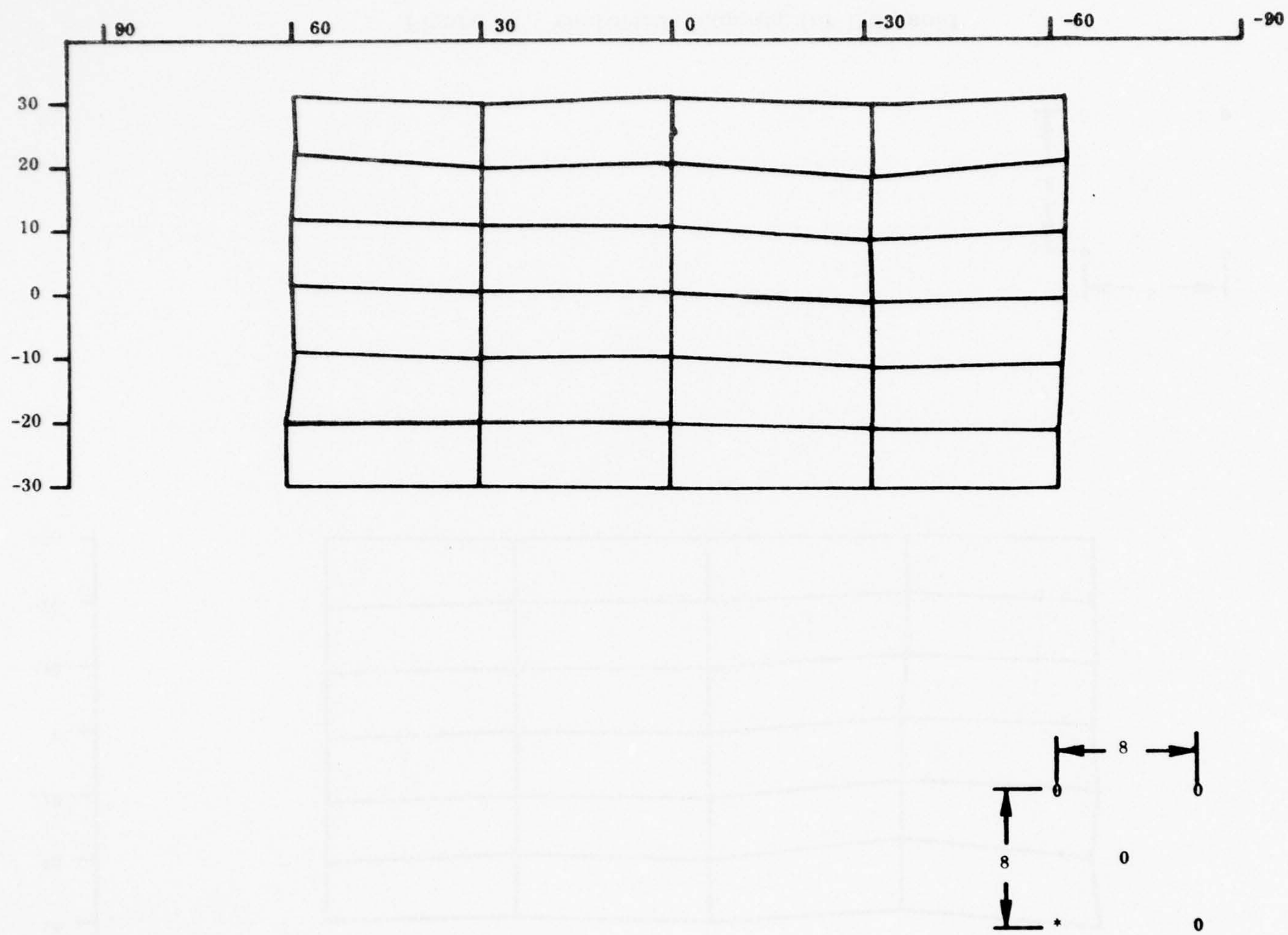


Figure 35. Distortion Mapping for Ellipsoid

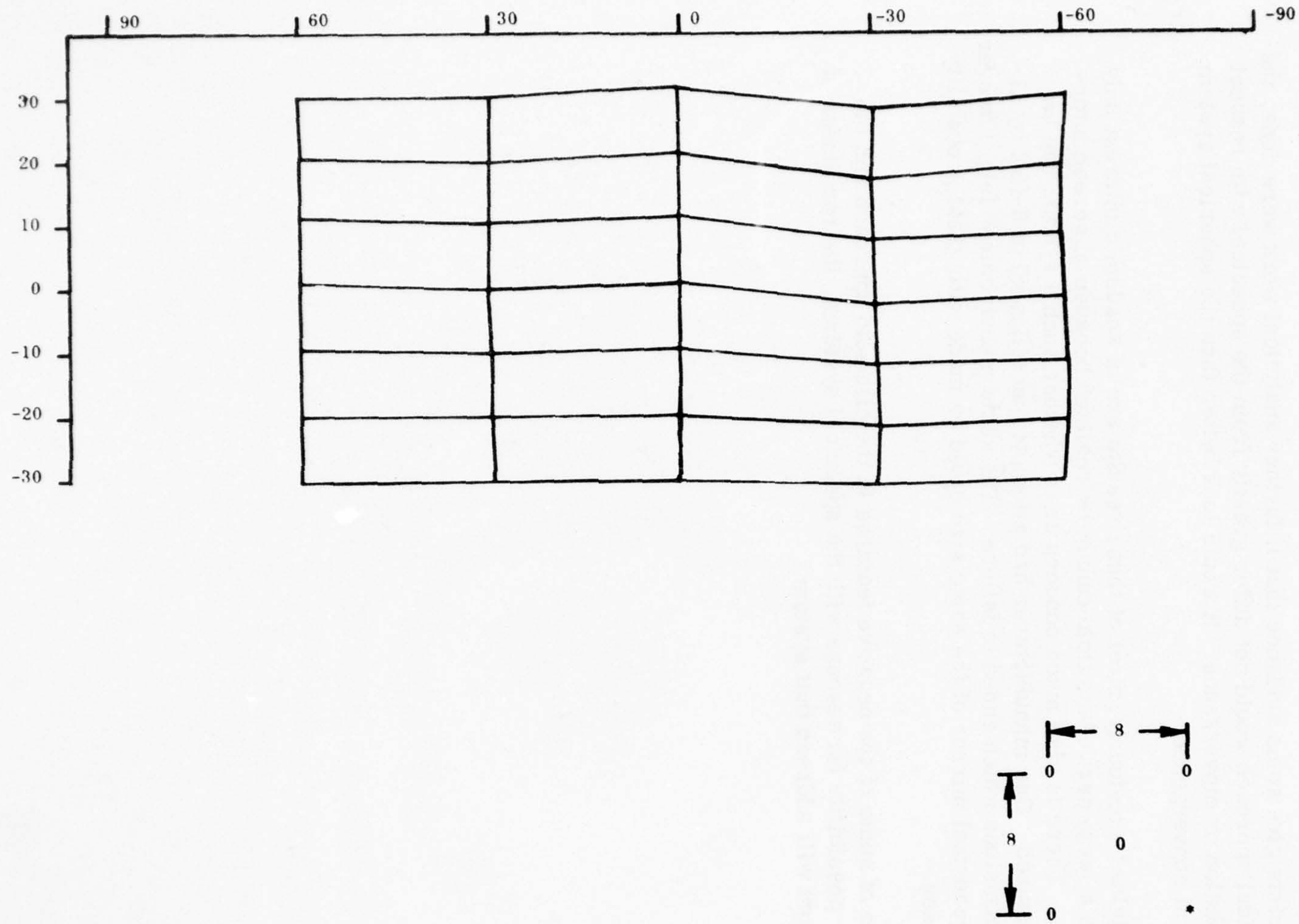


Figure 36. Distortion Mapping for Ellipsoid

plots have an unusual dip at -30 degrees azimuth that is not present in the spherical system.

These plots give some evidence that if further analytical work were done, the ellipsoidal approach would not differ greatly from the spherical with respect to resolution or dipvergence. It would look better than the spherical system in lateral convergence.

As explained previously, most of these results are of academic interest only because a large part of the field cannot be realized because of screen interference. There is also much concern as to whether such a system can be manufactured. One manufacturer had attempted an ellipsoid of 6-foot by 11-foot dimensions which ended in failure. The same manufacturer felt, however, that a spherical mirror of the same size could be made with great probability of success.

Because of some of the negative features in the ellipsoid approach and the greater possibility for success with the spherical systems, the remainder of the report will address that system.

SECTION 6

DESIGN OF PROJECTOR SECTION

The projector section starts with the rear-projection screen and the array of object points determined in Section 5. It is the requirement of this section to provide a continuous image on that rear-projection screen throughout its 180 degrees of azimuth and 60 degrees of elevation. The goal is to provide a highlight brightness of at least 6 footlamberts for the viewer and to keep fall-off to less than 25 percent. To eliminate distortion in the final display it is also required that the normal path of rays from the projectors be altered slightly to fit the array of object points from Section 5. This is referred to as predistorting the image.

The first step is to determine the number of projectors and types that might be needed. Several types of projection systems were considered, and the General Electric light valve was judged to be most suitable for this application. This projector is now capable of 800 readable television lines and 500 lumens output. Contrast is 25:1. The measured fall-off in the corners of the 4:3 aspect ratio field is about 75 percent. For a square field the fall-off in the corners is close to 50%. Color is an established capability. The package size and weight are also attractive. It has dimensions of 22 inches high by 17 inches wide by 30.5 inches long and weighs 130 pounds. Figures 37 and 38 are cross-section and plan views of the planned projector section.

The rear-projection screen has an area of 264 square feet. If three projectors are used, each projector will illuminate 88 square feet. The illumination at the center of one of these areas becomes 500/88 = 5.68 lumens/square feet. In order to achieve 6 footlamberts brightness at the center, screen gain must be 1.06. However, Figure 37 shows that the useful rays on the mirror side of the screen tend to make a sharp bend angle downward at the screen surface meaning that a lower gain screen must be used and that a gain of 1.06 cannot be attained for the directions shown. One particular rear-projection screen material has characteristics that at first appear ideal. It has a gain of 0.4 at 0-degree bend angle and only drops to 0.35 at 60 degrees. However, because of its low gain, the highlight brightness would not be greater than 2.3 footlamberts. The other drawback with low-gain screens is their high reflection factor. Light from one side of the screen would tend to wash out the image at the other side.

To obviate some of these difficulties either a projector with a higher lumen output must be used or modification of the screen must be made such that the

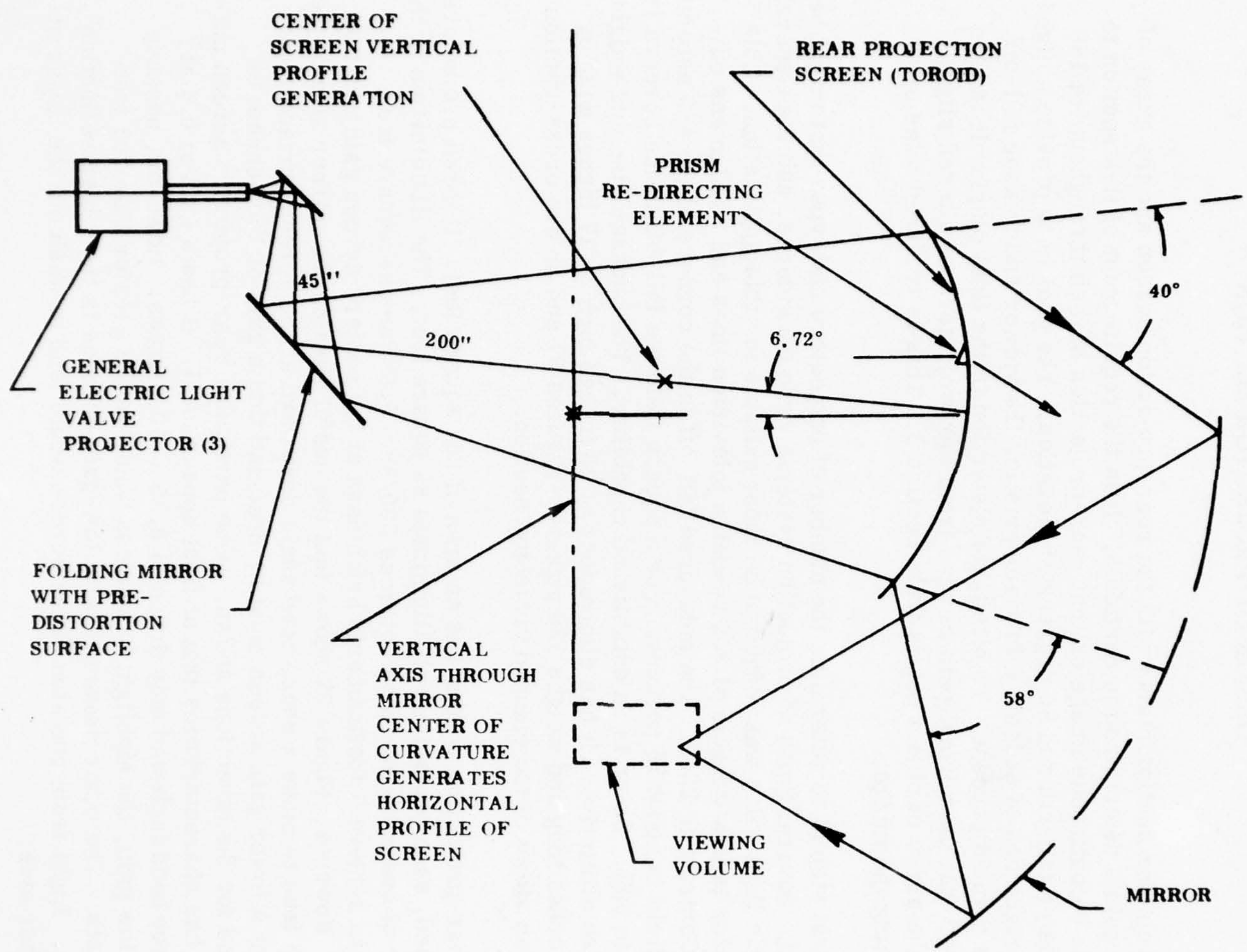


Figure 37. Projector Section Cross-Section

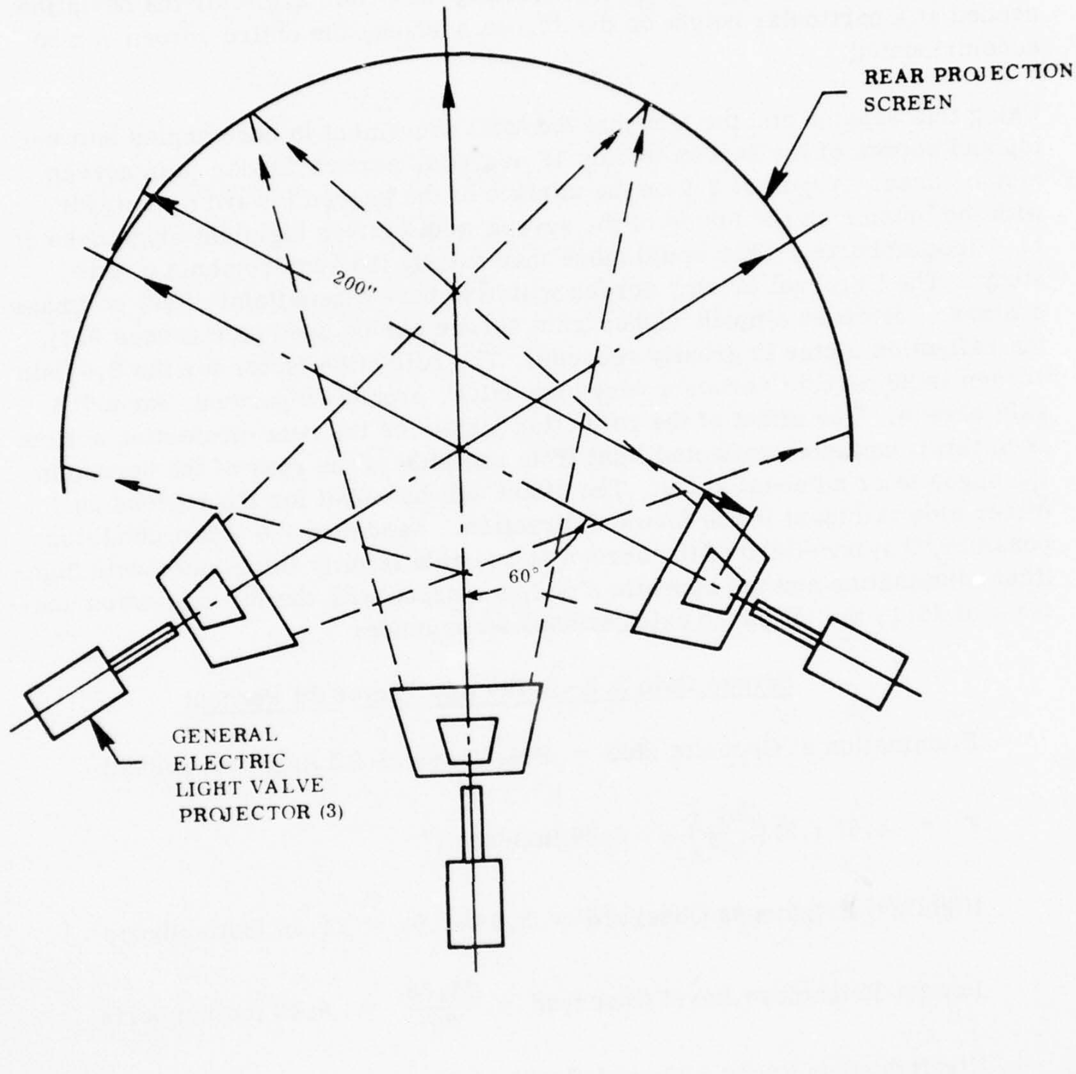


Figure 38. Projector Section Plan View

incident rays are deviated downward in addition to being diffused. Since the only candidate systems for high lumen output are monochrome types, and they have been ruled out, the second approach must be made. The screen surface can be modified with a lenticular subsurface of small individual prisms. Such is shown in Figure 37, or by imagining that prism as the cross-section of a long narrow prism that follows the screen periphery horizontally around its whole 180-degree extent. By making the prism strips narrower than the resolution interval (< 0.100 inches) and adjusting the prism angle for the deviation needed at a particular height on the screen surface, the entire screen can be accommodated.

Using this scheme and the fact that the total decrement in bend angles between top and bottom of the screen is only 18 degrees, a much higher gain screen may be used. A gain of 2.0 on the surface of the screen toward the mirror with the prisms on the inside of the screen would give a highlight brightness of 11.4 footlamberts. This would more than satisfy the requirements of this study. The "Fresnel prism" screen will also have a beneficial effect on image contrast. Because a much higher gain screen can be used (2.0 versus 0.4), the reflection factor is greatly reduced. The reflection factor for the 2.0 gain screen is 20 percent versus a very high value, around 70 percent, for a 0.4 gain screen. The effect of the reflection factor for the rear-projection screen is to throw unwanted reflected light from one side of the rear of the screen to the opposite or adjacent sides. The effect will be worst for the regions on either side and least in the forward direction. Assuming the worst conditions possible, that one-third of the screen at one side is fully illuminated with highlight illumination and the opposite side has a scene with the full television contrast of 25:1, the following calculations can be made:

<u>Screen Gain 2.0—Reflection Factor 20 Percent</u>

Illumination at Opposite Side = Brightness (Solid Angle Subtended)

$$E = 5.68\,(.2)\left(\frac{88}{19^2}\right) = 0.28 \text{ lumens/ft}^2$$

Highlight Brightness Observed = 5.68 (2.0) = 11.36 footlamberts

Lowest Brightness Level Observed = $\frac{11.36}{25}$ = 0.45 footlamberts

Highlight Brightness + Unwanted Fill Light

= 11.36 + 0.56 = 11.92 footlamberts

$$\text{Lowest Brightness} + \text{Unwanted Fill Light} = 0.45 + 0.56 = 1.01 \text{ footlamberts}$$

$$\text{New Contrast (worst)} = \frac{11.92}{1.01} = 12{:}1$$

Screen Gain 0.4—Reflection Factor 70 Percent

Illumination at Opposite Side = Brightness (Solid Angle Subtended)

$$E = 5.68\,(.7)\left(\frac{88}{19^2}\right) = 0.98 \text{ lumens/ft}^2$$

$$\text{Highlight Brightness Observed} = 5.68\,(0.4) = 2.27 \text{ footlamberts}$$

$$\text{Lowest Brightness Level Observed} = \frac{2.27}{25} = 0.09 \text{ footlamberts}$$

$$\text{Highlight Brightness} + \text{Unwanted Fill Light} = 2.27 + 0.39 = 2.66 \text{ footlamberts}$$

$$\text{Lowest Brightness} + \text{Unwanted Fill Light} = 0.09 + 0.39 = 0.48 \text{ footlamberts}$$

$$\text{New Contrast (worst)} = \frac{2.66}{0.48} = 5.5{:}1$$

The very worst condition using the "Fresnel prism" screen is about 12:1 contrast versus a desired value of 20:1. Using the diffusion-only low-gain screen, the effect is significant. About 5.5:1 contrast remains at the sides of the screen. Because the small prism strip angles are tailored to their position on the screen and because the screen is a figure of revolution generated about the vertical axis shown, the greatest bend angle encountered will be about 20 degrees due to the variation of observer position within the viewing volume.

The light valve projection fall-off in the extreme corners of its 4:3 aspect ratio field is 75 percent. The raster, in this application, is of 1:1 aspect ratio and, as such, has about 50 percent fall-off in its corners. Fortunately, the eye's response to luminance is not linear but is close to logarithmic. Gradual luminance differences of as much as 2:1 will appear to be quite uniform.

The standard General Electric light valve projector lens has a focal length of 3 inches and a raster height of 0.825 inch. If this lens system were used directly, the projector would have to be located about 31 feet from the screen. This system would be too bulky and unwieldy.

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WIDE-ANGLE, MULTIVIEWER INFINITY DISPLAY DESIGN. (U)
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The situation can be corrected by relaying the light valve image to an intermediate location where it can be reimaged by a lens selected for the desired projection throw. The intermediate image also permits masking around its periphery to "fit" the projected image to the 60-degree by 60-degree dimensions of the rear-projection screen and, even more importantly, to obtain exact edge continuity with the screen image from the adjacent channel. The relay system is shown in cross-section in Figure 39 and schematically in Figures 37 and 38 as a long tube extending from the light valve projectors. The throw distance for this arrangement is 260 inches as shown in the folded configuration of Figure 37. The intermediate image arrangement also provides the capability for adding a lens near the image plane that can be used to adjust the projected field curvature to that of the rear-projection screen if the depth of focus is not sufficient.

The General Electric color light valve projector is capable of 800 readable television lines. This is equivalent to 4.5 arc minutes between lines over the 60-degree vertical field. The MTF for the projector is stated to be about 0.40 for 800 television lines. This coupled with the 0.90 MTF for the Display section gives a total MTF of 0.36 at 4.5 arc minutes. This more than satisfies the 6 arc-minute resolution requirement.

The remaining consideration for the Projector section is the pre-distortion input. Although pre-distortion might be inserted in the CIG directly or in the television scan drive, it is least offensive to all subsystems to apply it as a gently reshaped folding mirror surface in each projector path. The particular mirror surface for this purpose is identified in Figure 37.

Figure 40 is a plot of the pre-distortion that is needed. It is not a plot of the screen surface directly but a projection of the screen point intersections into the screen vertex plane. The round spots are the locations of the object points in the screen determined in Section 5. They are the desired image point locations. The crosses are the locations of the intersections of the chief rays from an ideal lens at the light valve projector. The concept of the ideal lens is not far from correct because the General Electric light valve distortion is very low.

This ray trace furnished part of the data needed to design the pre-distortion surface. In effect the ray directions are allowed to remain intact up to the planned mirror pre-distortion surface. The normal at each local chief ray mirror intersection is then altered slightly in direction to redirect the ray to the chosen object target point in the screen found in Section 5.

Corresponding to the spot locations in Figure 40, Table 16 lists the direction cosines and angles that the new normals must make with the normal of the old, completely flat mirror surface. In that surface the Z-axis is the normal.

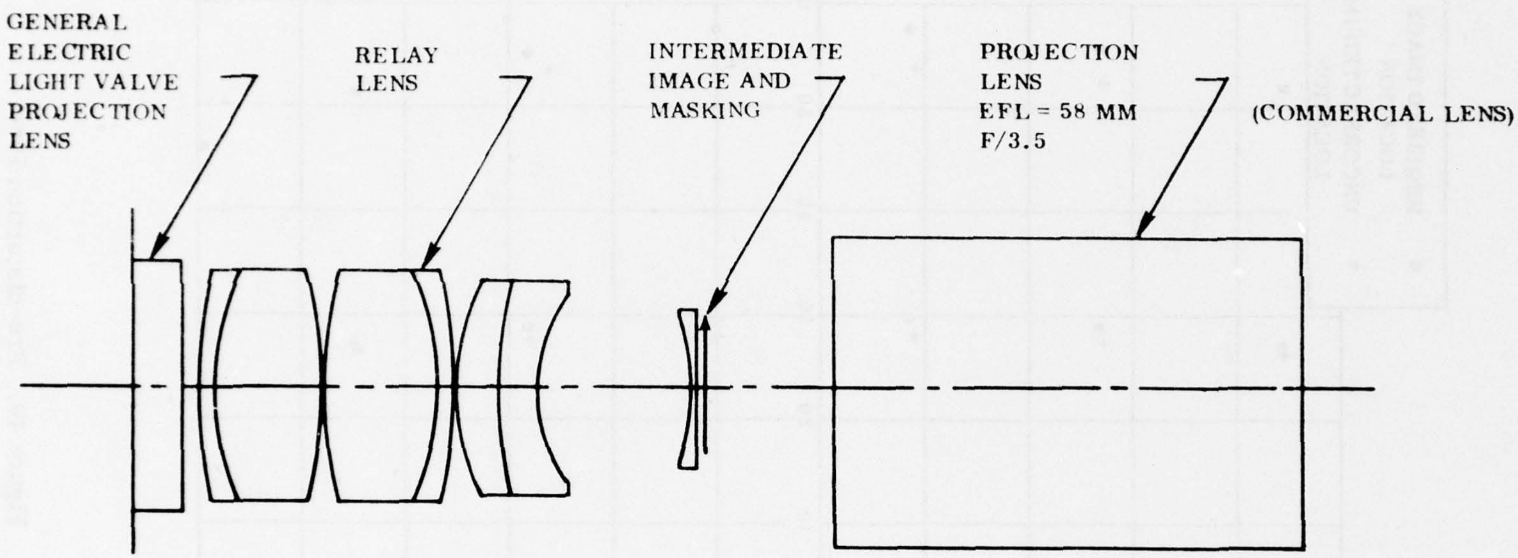

Figure 39. Projector Lens Relay System

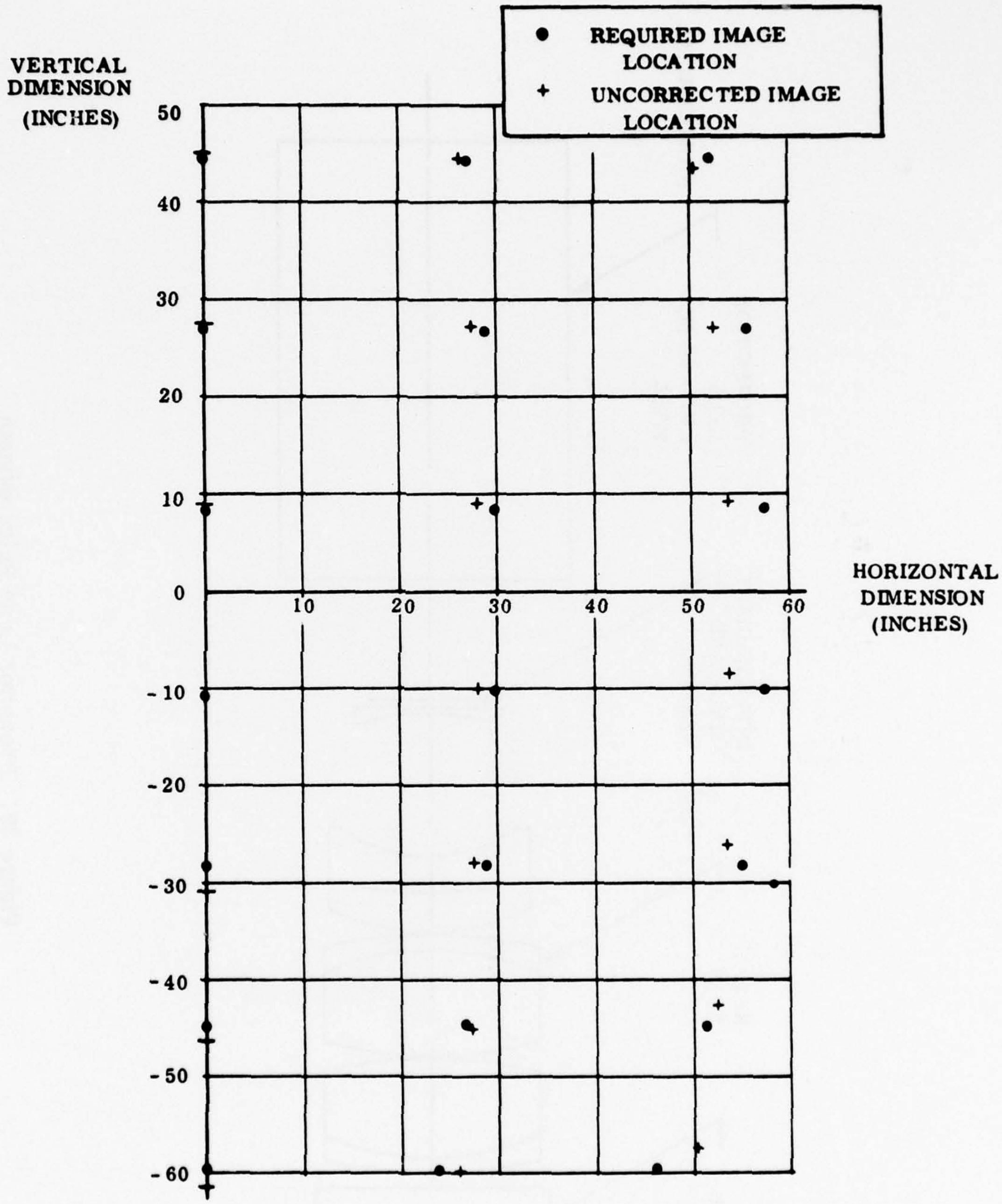

Figure 40. Pre-distortion Plot

Table 16. Pre-distortion Mirror Shaping Data

Coordinates In Screen From Figure 40		Coordinates in Mirror Surface		Direction Cosines of Normal			Angle Between Normal and Normal to Flat Surface
X	Y	X	Y	NX	NY	NZ	Angle
0	43.95	0	15.880	0	-0.00110	1	0°
26.865	43.95	5.275	15.880	-0.00202	-0.00011	1	0.088°
51.9	43.95	10.551	15.880	-0.00531	0.00318	0.99998	0.340°
0	26.45	0	11.333	0	-0.00149	0.99999	0.191°
28.82	26.45	5.648	11.333	-0.00507	-0.00093	0.99999	0.252°
55.675	26.45	11.296	11.333	-0.01199	0.00124	0.99989	0.846°
0	8.19	0	6.099	0	-0.00074	1	0°
29.86	8.19	6.077	6.099	-0.00678	-0.00066	0.99998	0.351°
57.685	8.19	12.154	6.099	-0.01557	-0.00013	0.99988	0.891°
0	-10.45	0	0	0	0	1	0°
29.712	-10.45	6.577	0	-0.00619	-0.00164	0.99998	0.107°
57.4	-10.45	13.153	0	-0.01455	-0.00236	0.99989	0.851°
0	-28.35	0	-7.191	0	0.00152	0.99999	0.187°
28.625	-28.35	7.166	-7.191	-0.00325	-0.00004	0.99999	0.189°
55.3	-28.35	14.331	-7.191	-0.00857	-0.00467	0.99995	0.582°
0	-44.85	0	-15.791	0	0.00345	0.99999	0.183°
26.596	-44.85	7.870	-15.791	0.00326	0.00069	0.99999	0.202°
51.38	-44.85	15.740	-15.791	0.00595	-0.00723	0.99996	0.534°
0	-59.45	0	-26.274	0	0.00643	0.99998	0.337°
23.993	-59.45	8.729	-26.274	0.01444	0.00216	0.99989	0.836°
46.35	-59.45	17.458	-26.274	0.02863	-0.01111	0.99953	1.766°

Table 16 also includes the coordinates of the particular ray referred to in Figure 40 and the coordinates of the ray at the mirror for surface computation.

It can be seen that the pre-distortion surface is a very weak variation from flatness. All but one of the normals depart from flatness by less than 1 degree.

The actual mathematical exercise of determining the equation for the surface was not done. The procedure is to assign a general form of surface equation that does not assume rotational symmetry. Such an equation would be like the following:

$$Z = g(x, y)$$

where Z is the departure of the surface from a flat reference level and,

$$g(x, y) = d_{01} (d_{06} x^2 + y^2) + d_{02} (d_{07} x^2 + y^2)^2 + d_{03} (d_{08} x^2 + y^2)^3 + d_{04} (d_{09} x^2 + y^2)^4 + \ldots$$

If the surface equation is put in the form,

$$O = Z - g(x, y)$$

the normal vectors take on the form,

$$\vec{M} = \vec{i} \frac{\partial g}{\partial x} + \vec{j} \frac{\partial g}{\partial y} - \vec{k}$$

The partial derivatives are simply direction numbers of the normal vector and are proportional to the values listed in Table 16. These tabular values are equated to the expressions for $\partial g/\partial x$ and $\partial g/\partial y$ from the equation above. The corresponding x, y coordinates for the location of the appropriate normals are also entered into the expressions. This leaves a group of equations in which the only unknowns are the coefficients d_{01}, d_{02}, etc. The solution of possibly 10 of these expressions for 10 unknown coefficients can be done by computer analysis. It was not done because the solution is costly and time-consuming and adds very little to the understanding of the design.

SECTION 7

MANUFACTURING METHODS FOR MIRROR AND SCREEN

7.1 MIRROR

Discussions with vendors have revealed three different processes that might be used for manufacturing the large concave spherical mirror. All approaches obviously depend on the mosaicking of mirror segments because of the large dimensions of the main mirror.

The dimensions of the mirror will be given again for reference. The mirror is a portion of a spherical surface of 16-foot (192-inch) radius. The equator may be imagined to be horizontal and 16 feet from the bottom of the sphere. The top edge of the mirror is 20 inches above and the bottom edge 160 inches below the equator. The mirror occupies only 180 degrees, half of the described spherical zone. The area is 754 square feet.

One of the three mirror-making methods uses cast epoxy on a rigid honeycomb aluminum preform. Another method employs electroforming, or the production of an electro-deposited nickel shell on a master surface. The third method slumps glass to shape, attaches it to a rigid aluminum preform, and optically grinds and polishes the surface.

The first method is generally described by Cavaliere[5]. Figure 41, explaining the process, is excerpted from that report. It is basically self-explanatory. The master is preferably made of stainless steel. Copper is used as a parting agent.

For this application one approach would employ 14 mirror sections, seven distributed along the bottom half and seven along the top half of the main mirror. The seven bottom sections would be identical in shape as would the seven top pieces. Each section would have dimensions approximately 7-feet wide by 8-feet high. The preform backing would be of honeycomb construction and have a thickness of 6 1/2 inches. Other characteristics are discussed in Section 8. The cost is moderately high.

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[5] Cavaliere, Richard, J., et al, "The Process and Techniques of Manufacturing Replica Mirrors (Cast Epoxy)," U.S. Army Armament Command, Frankford Arsenal, AD-A021/86, April, 1975.

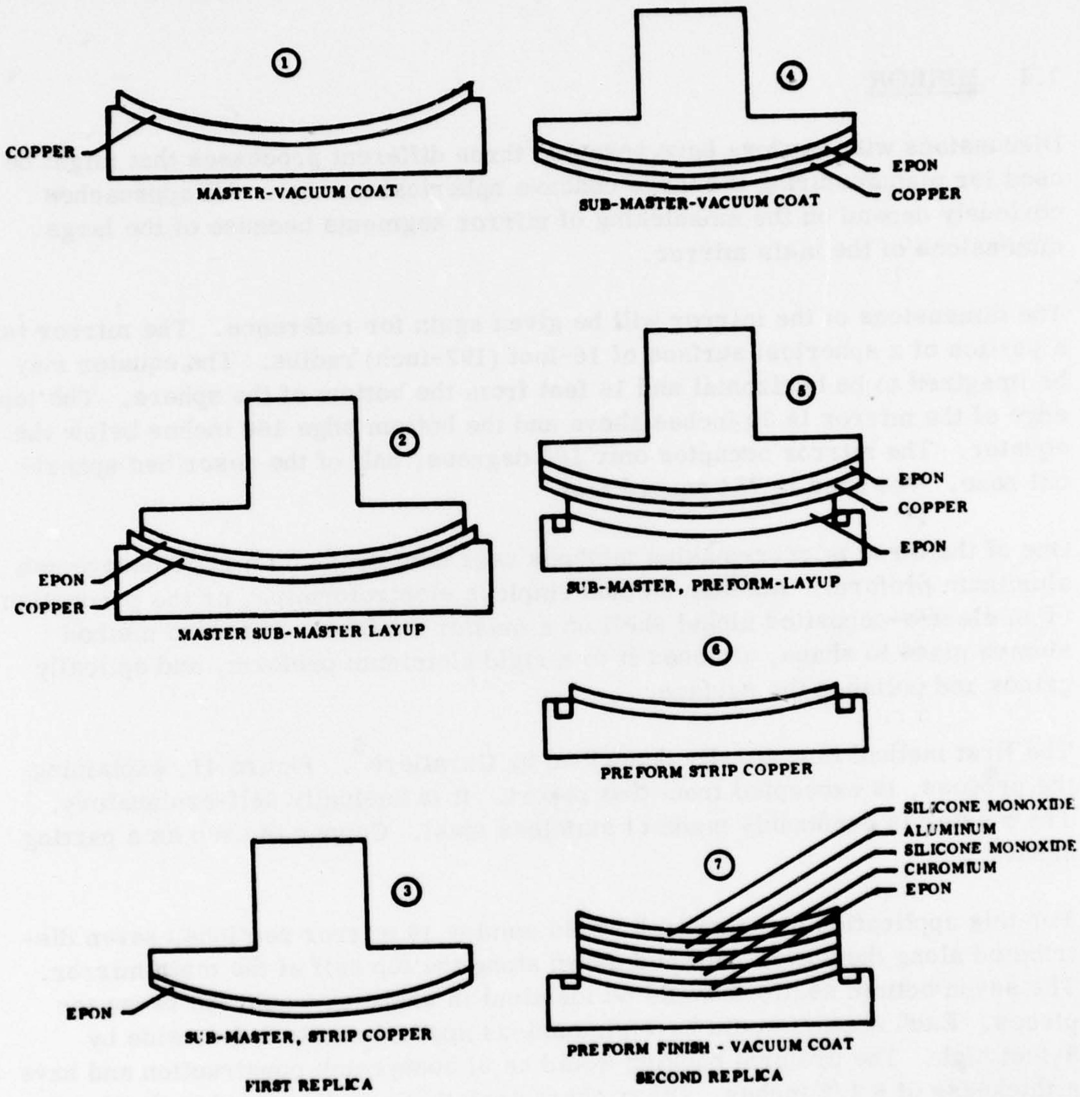


Figure 41. Cast Epoxy Replication Process

The advantage of the cast epoxy approach is that each mirror segment is a structural element in itself that can be aligned in a skeleton framework. It is also attractive from the standpoint of surface quality, which may be better than 1-arc minute slope error over any segment.

The concept employing electroformed mirror segments requires mounting of the shell segments to a structurally sound backing such as the aluminized domes manufactured for planetariums. In that concept the supporting structure would be a formed aluminum sheet, partial dome on which the electroformed segment would be bonded or fastened. Optical alignment of the individual segments would be done by shimming before bonding or fastening.

The electroformed segments, as suggested by one company, might be 40-inch wide hexagons made of nickel 0.060 to -0.100 inch thick with evaporated aluminum and silicon monoxide coatings. Seventy-eight of these hexagonal segments would be required. The cost is relatively low.

The cost of the electroformed approach is more attractive but the probable surface accuracy for each segment is of concern. It is also very questionable whether the alignment of 78 segments could ever be satisfactorily accomplished. Perhaps the use of larger mirror segments would make the approach more competitive. Another electroforming vendor has described 6 1/2-foot by 6 1/2-foot segments. This size would require something like 18 segments, which might be an improvement. The cost is moderately high. In this case support structure would be bonded onto the mirror segments for maintaining stiffness and for alignment hardware support.

In the third method, the main mirror would be made up of 22 essentially square segments (69 11/32 inches by 74 29/32 inches). Each segment would be made from an 11-foot diameter dished glass blank that is attached to an aluminum preform. The radius of curvature of the segment would be in the vicinity of 192 inches.

The glass and aluminum preform would each have a thickness of 0.5 inches so that a cross-section would have a total thickness of 1 inch. Mounting hardware would be attached to the aluminum preform and the whole segment fastened to the mounting structural members. Optical alignment would be done to all 22 segments.

This approach would undoubtedly produce the best optical surface because of the optical grinding and polishing of glass. Its main drawbacks are its weight and probable cost. The weight will be discussed in Section 8.

There are many other methods that could be envisioned or discovered in a vendor search for producing a large mirror such as described. Most of the methods would be variations of those discussed. The entire process is on the

fringes of the so-called "state of the art." It is believed, however, that as display devices become more complex and are required for simulating larger training stations, the demand for large optical surfaces will increase. Research into this field should be rewarding.

7.2 SCREEN

The rear-projection screen is a toroidal surface. Its radius in the vertical direction is 89.27 inches and its generating radius about a vertical axis, 115.37 inches. The screen wraps around 180 degrees in the horizontal direction. Its area is 264 square feet. The material of the screen must have high optical transmission and must not exhibit any discontinuities over its full extent.

The material that appears best suited for the purpose is acrylic. Discussions with one vendor suggested that they expected no great difficulties in its manufacture. They described the material as 1/4-inch-thick acrylic formed over molds to the required shape. It was also suggested that, in the interest of economy, the screen should be made up of two or more similar pieces. Edge processing and matching is not expected to be a problem.

In addition to the basic screen material a diffuse surface must be applied, and as stated previously, possibly a "Fresnel-lens"-type prism surface. Although these aspects were not pursued, the application of a flexible sheet of plastic material to the mirror side surface of the screen, to provide the proper amount of diffusion, is not expected to be a great problem. The surface might also be formed by spraying the convex side of the acrylic form with ethyl cellulose, or similar material, containing white diffusing pigment of the correct amount.

If necessary, the Fresnel prism structure would most likely be applied by bonding thin transparent acrylic cast sheets of the material onto the concave side of the base screen. The transparent prism sheets would be formed by the same techniques used for producing Fresnel lenses. The differences are that the sheets might be thinner for more flexibility and the grooves would not be arcs of circles but parallel and straight. In all likelihood, for this application, the prism cross sections would be uniform over the whole screen because there is a difference of deviation required of only 18 degrees between top and bottom.

SECTION 8

MECHANICAL STRUCTURE DESIGN

8.1 DESIGN CONCEPT

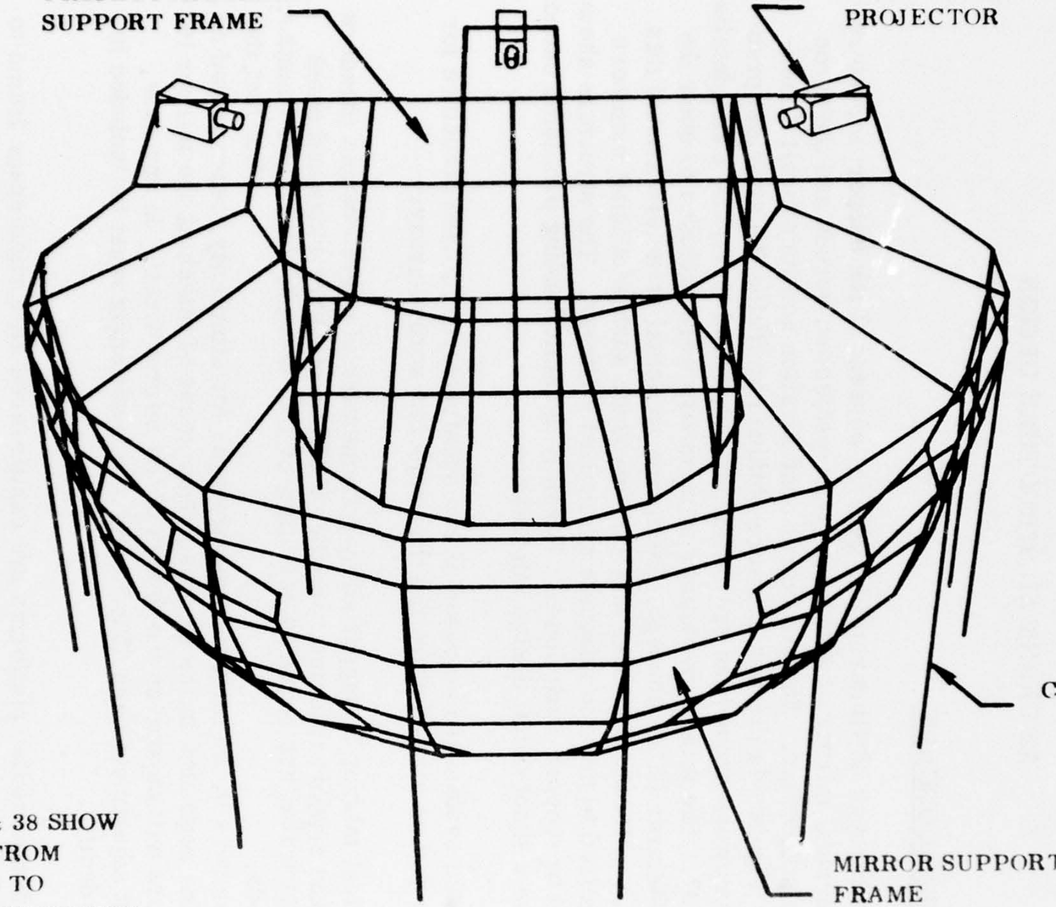
Figures 42 through 46 illustrate the general concept of the support structure for the spherical mirror, the toroidal rear-projection screen and the three light valve projectors. The structural configuration and its overall dimensions (see Figures 44 through 46) were obtained by fitting the simplest practicable framework around the spatial layout illustrated in Figure 1 and detailed in Figure 37. The minimum number of members were included to show the essential features of the concept. Designing an actual structure around this concept may relocate members and will introduce such additional members as are required to provide adequate structural stiffness. The structure shown is intended to support static loads. Possibly dynamic loading problems cannot be analyzed without detail design information.

The proposed system is composed of two substructures, a fore structure for the mirror and an aft structure for the projector-screen array.

The spherical mirror is supported by a framework of curved beams (headers and ribs) and support columns, together with any stiffener rings and panel cross bracing that are required per state-of-the-art spherical dome construction methods. Note that the curved members in the mirror structure are, for simplicity, represented as straight-line segments in the figures. The means of attaching the mirror to the structure will depend on the design of the mirror itself. In any case, three-point adjustment capability for mirror positioning must be included in the design details.

Two rigid semicircular platforms are cantilevered off a rigid space frame to support the toroidal rear-projection screen. The platforms must be of cantilever design since the vertical support structure beneath either one of them would lie in optical paths. The three projectors sit on top of the screen support framework, and the light rays are directed downward and toward the screen by mirrors, as shown in Figures 37, 38, and 45.

The fore and aft structures are tied together by members joining points around the top of the mirror framework to points around the semicircular upper platform of the screen support. These radially arrayed members might be rigid angular extensions of the circumferential support columns. As such they could



NOTE: FIGUTES 37 & 38 SHOW RAY PATHS FROM PROJECTORS TO TOROIDAL PROJECTION SCREEN

Figure 42. Wide-Angle Display Support Structure Concept. Fore-Aft Perspective

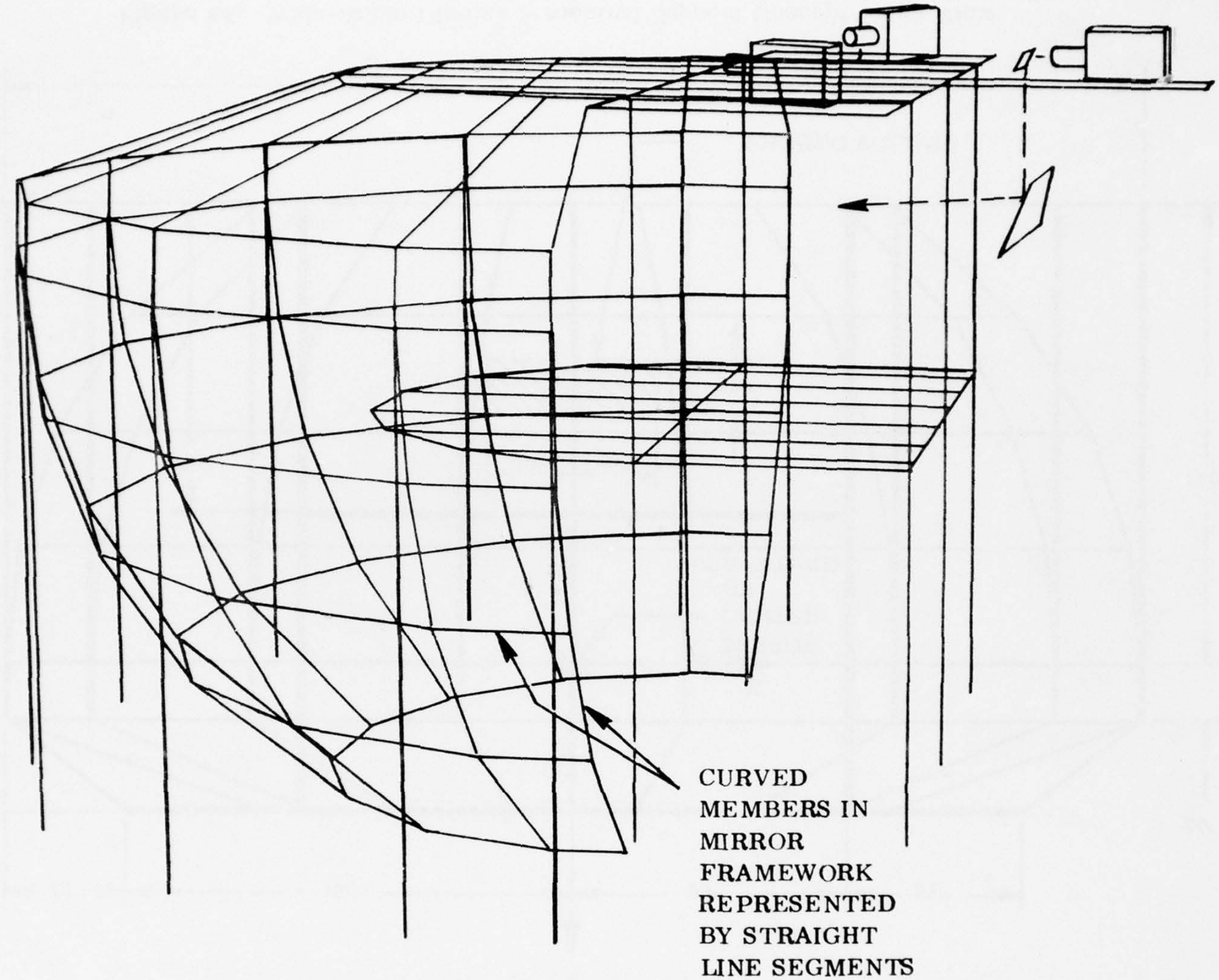


Figure 43. Wide-Angle Display Support Structure Concept Lateral Perspective

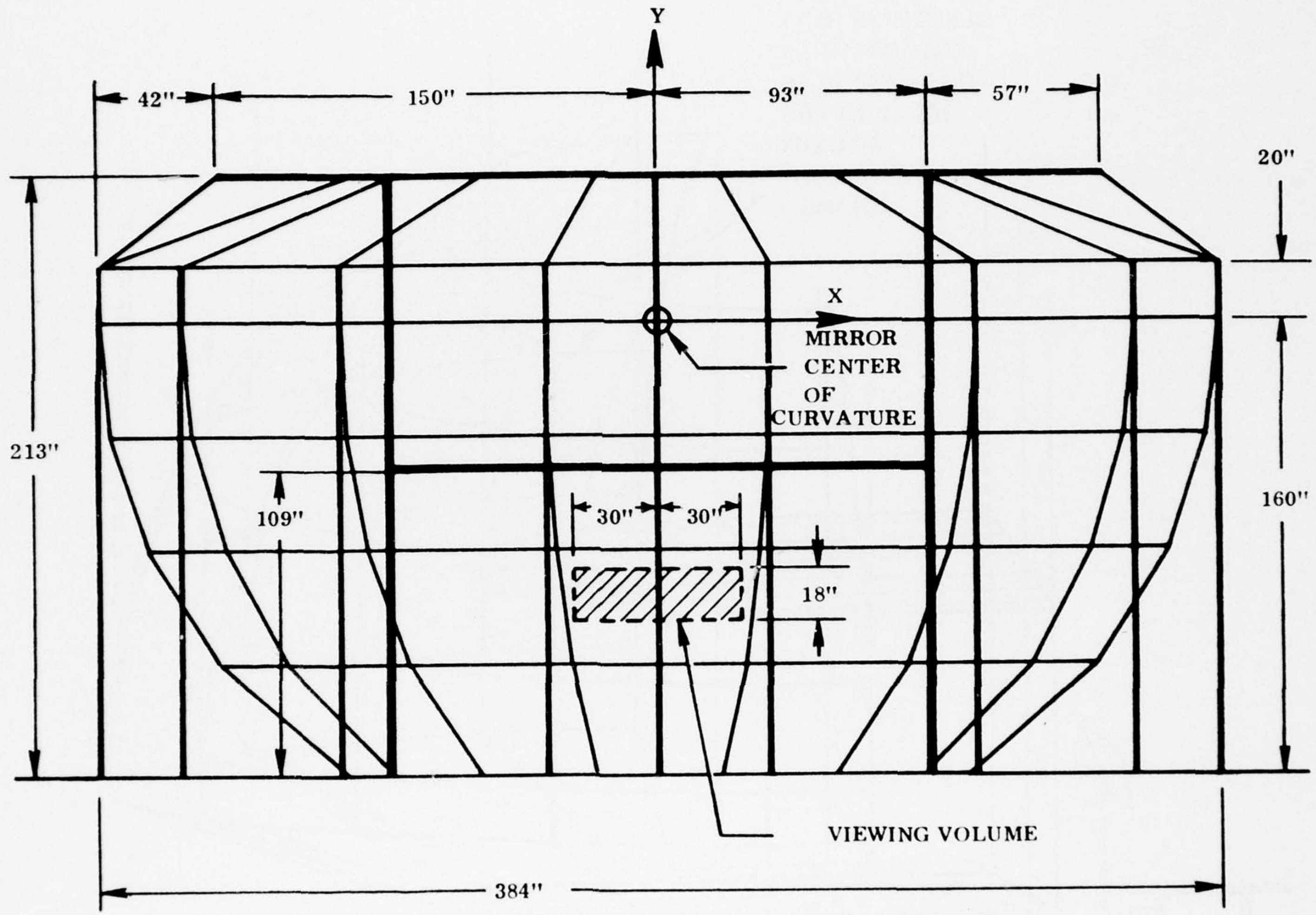


Figure 44. Wide-Angle Display Structural Support Concept Front View

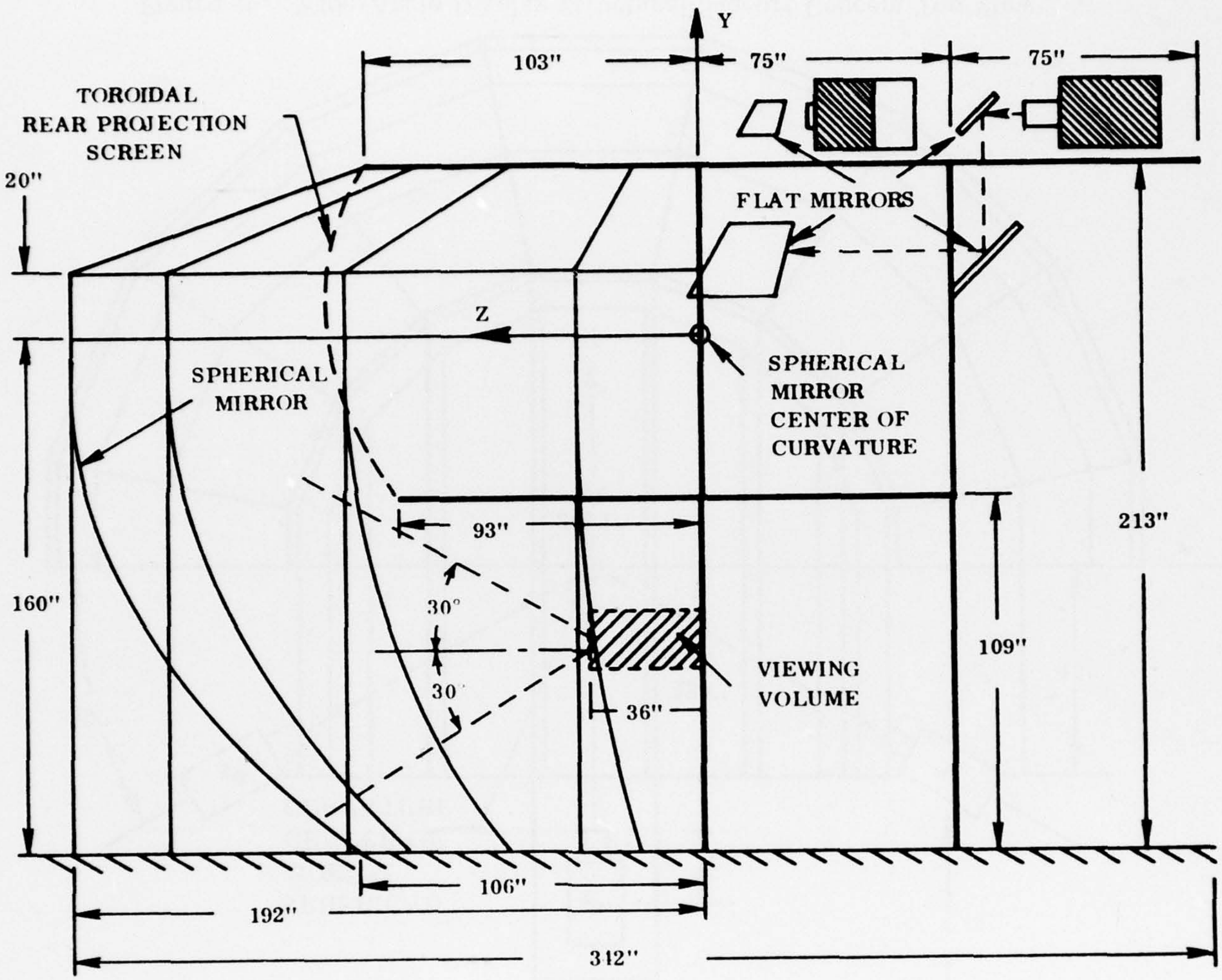


Figure 45. Wide-Angle Display Structural Support Concept Side View

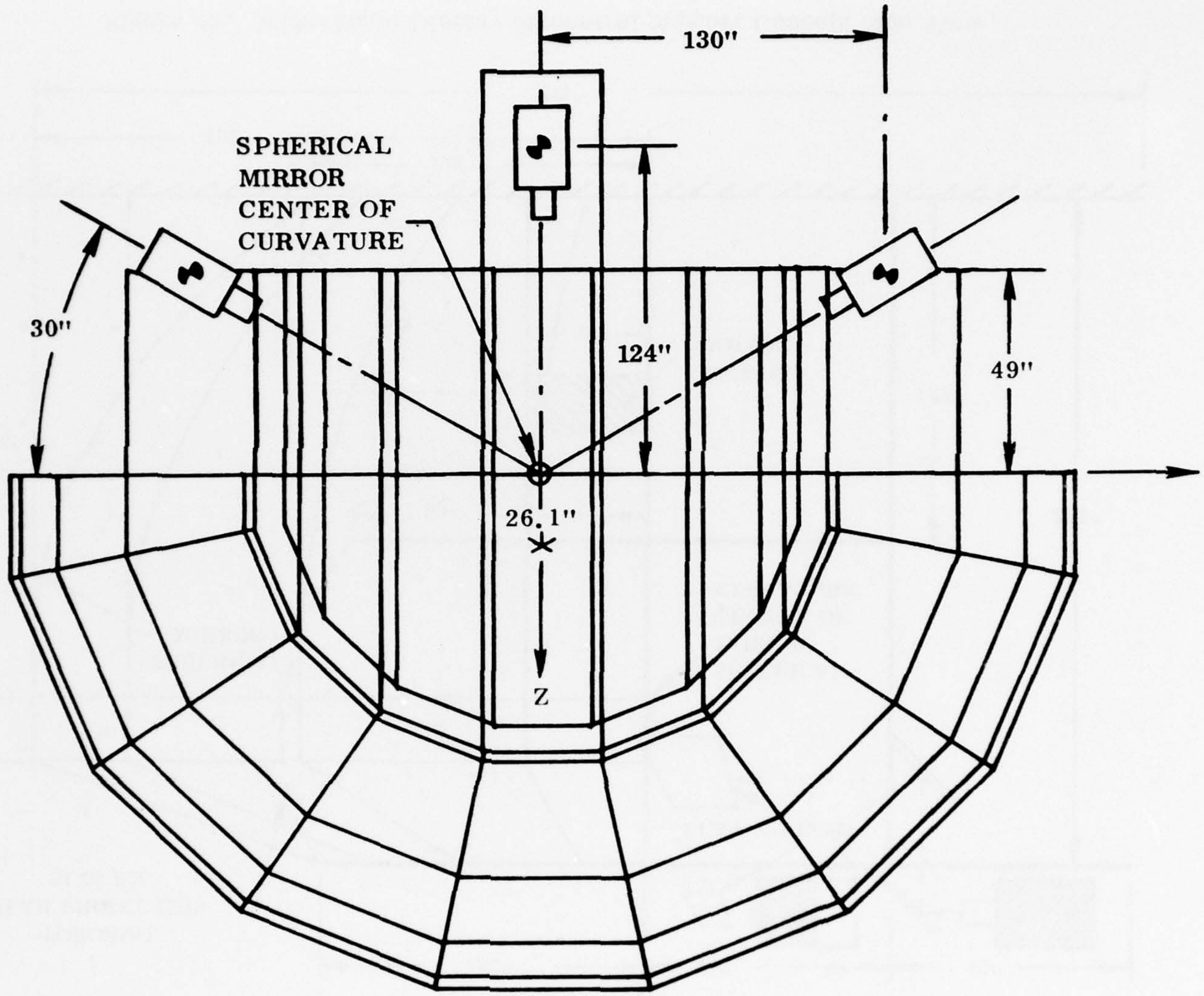


Figure 46. Wide-Angle Display Structural Support Concept Top View

be designed to provide significant vertical support to the upper platform. If so, the screen could be hung from the upper platform and only retained by the lower one. This would be an alternative to placing the weight of the screen on the lower platform if doing so would require girders beneath the lower platform of such a depth as to lie within the +30-degree view ray from the viewing volume (see Figures 37 and 45).

It should be observed that if the simulator is to sit on a rigid, fixed floor, then the cockpit structure enclosing the viewing volume (see Figures 44 and 45) can be completely independent of and isolated from the display structure, thus avoiding, for example, vibration transfer.

If the display is to sit on a motion platform, then it is clear that an effort will have to be made to reduce the area enclosed by the base of the structure. As depicted herein, this area is approximately 32 feet wide by 22 feet long. If the support columns were deleted from around the circumference of the mirror framework, the base area would be reduced to approximately 18 feet wide by 15 feet long. In that case curved beams of large section modulus would have to be fabricated and placed vertically around the mirror circumference. These ring-like members would be attached to a rigid structure formed around the base of the mirror, and they would be braced by several semicircular horizontal rings encircling the mirror. This more complex design concept will not be explored further here, except to note that it would likely be much more massive than the one employing support columns.

8.2 MASS AND MASS MOMENT ESTIMATES

In this section the weight, center of gravity (CG) and moments of inertia are found for the projector array, the screen, the mirror and the support structure. Using this information, the CG and moments for the complete assembly can be computed. The coordinate system used for the calculations is centered at the mirror's center of curvature (see Figures 44 - 46). The z-axis (roll axis) is directed forward toward the mirror; the y-axis (yaw axis) is directed vertically upward; the x-axis (pitch axis) completes the right-hand triad. The moments of inertia are given in each case with respect to parallel axes through each object's CG.

8.2.1 PROJECTORS

The three light valve projectors weigh 130 pounds each and their respective CG's are at the following (x, y, z) locations (see Figure 46) (±130", 67", -49"), (0", 67", -124").

Therefore, for this system:

Weight	390 lbs
CG	(0", 67", -74")
CG Moments of Inertia	
Roll	132 lb-ft-sec^2
Pitch	104 lb-ft-sec^2

8.2.2 SCREEN

The rear-projection screen is made of 0.25-inch plexiglas (specific gravity 1.2). Using the dimensions shown in Figure 37, exact mathematical calculations on the toroidal shape yield:

Weight	419 lbs
CG	(0", 1.55", 69.6")
CG Moments of Inertia	
Roll	625 lb-ft-sec^2
Pitch	189 lb-ft-sec^2

8.2.3 MIRROR

Let W_S be the weight per unit surface area of the mirror, in lb/ft^2. Using the dimensions shown in Figure 37, exact mathematical calculations on the spherical shape yield:

Weight	754 W_S lb
CG	(0", -69.3", 107")
CG Moments of Inertia	
Roll	2820 W_S lb-ft-sec^2
Pitch	951 W_S lb-ft-sec^2

8.2.4 SUPPORT STRUCTURE

The structure shown in the figures consists of 172 straight-line segments. Treating these idealized structural members as slender bars, all having the same weight per unit length W_L, in lb/ft, yields the following:

Weight	1090 W_L lb
CG	(0", -33.4", 52.2")
CG Moments of Inertia	
Roll	3950 W_L lb-ft-sec^2
Pitch	2620 W_L lb-ft-sec^2

There are at least three different ways of forming the spherical mirror. These are listed below together with their approximate weight per unit area, W_S, in lb/ft^2.

Aluminized nickel, 0.060 inch thick	2.8 lb/ft^2
Cast epoxy on aluminum honeycomb structure	8 lb/ft^2
0.5 inch glass on 0.5 inch aluminum	14 lb/ft^2

Choosing the smallest W_S yields a mirror weighing 754 by 2.8 = 2100 lbs. This plus the weight of the screen (419 lbs) and the projectors (390 lbs) amounts to 2900 lbs. To this must be added the support structure weight.

Using aluminum as structural material, a beam weight of W_L = 3 lb/ft would probably be a minimum to provide adequate stiffness throughout the structure. This weight is representative of that of a 5 or 6-inch-deep I-beam. Using this value as an average linear weight density for the entire structure yields a total structure weight of 1087 $\times$ 3 = 3260 lbs.

Combining the above separate weight, CG and inertia calculations yields, for the complete structure plus supported optical equipment:

Weight	6160 lbs
CG	(0", -36.7", 63.8")

CG Moments of Inertia

Roll	21800 lb/ft/sec^2
Pitch	14600 lb/ft/sec^2

Carrying out the same calculations using the heavy glass mirror instead (W_S = 14 lb/ft^2) yields:

Weight	14600 lbs
CG	(0", -55.6", 88.9")

CG Moments of Inertia

Roll	54400 lb-ft-sec^2
Pitch	27500 lb-ft-sec^2

Note that the CG is 123" above the base of the structure if the light mirror is employed and 104" above the base for the heavy mirror. Therefore, the moment of inertia about a parallel roll axis in the plane of the base is 42000 lb-ft-sec^2 for the display with the nickel mirror and 89000 lb-ft-sec^2 using the glass mirror, while the pitch moments are 35000 lb-ft-sec^2 and 62000 lb-ft-sec^2, *respectively*.

These numbers can be compared to performance limits of a hypothetical six-degree-of-freedom motion platform. Such a platform can drive a payload, including cockpit, of 18000 lbs., with a maximum total payload inertia of 35000 lb-ft-sec^2 about the platform plane. Since the calculations performed above did not include the cockpit structure and likely involved a conservative estimate of display support structure weight, it is clear that the wide-angle display could not be driven by a platform with the capacity of this example. This conclusion is reinforced when one considers that the base area of the proposed system, without support columns (and therefore much more massive than the structure analyzed above) is 270 ft^2, compared to a platform area of about 60 ft^2 for this example.

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